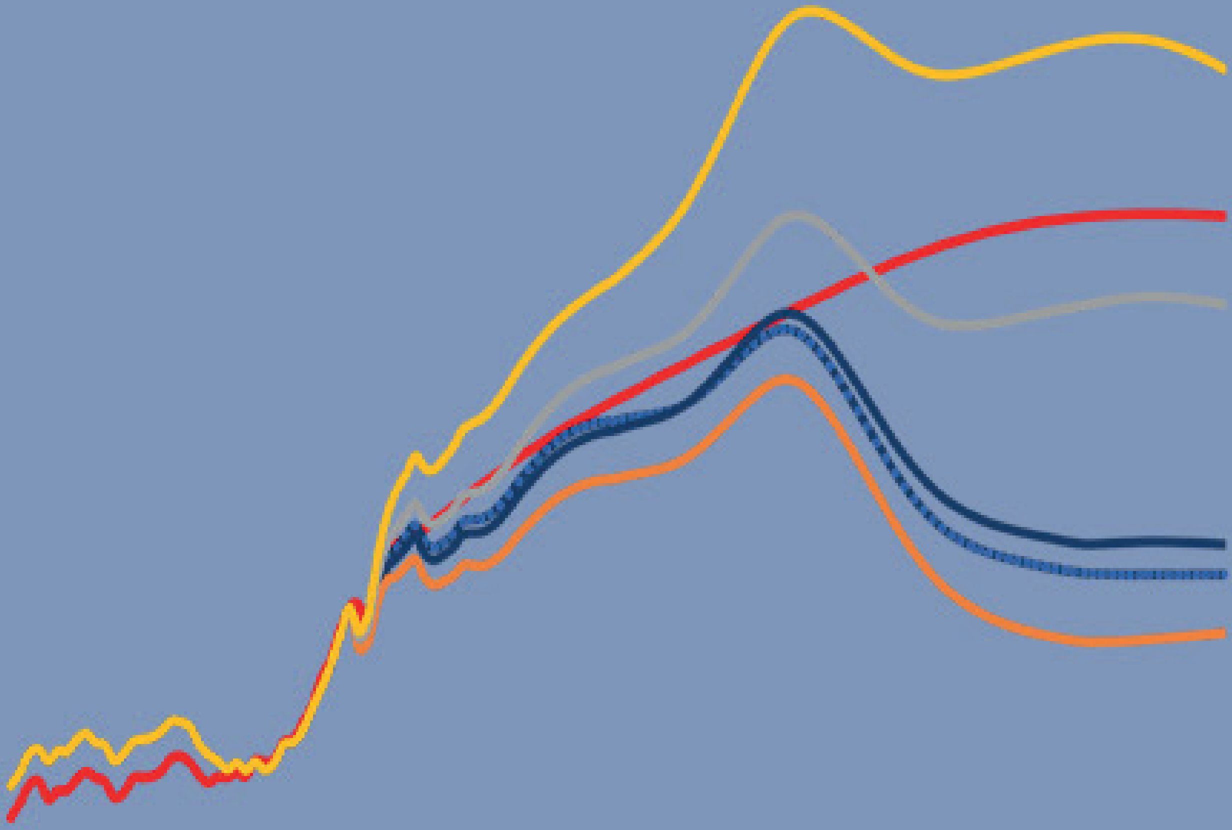
FROM BASELINES
IMPROVING
TO
THE MODELING OF
DEEP REDUCTIONS
INDUSTRIAL
ENERGY
DEMAND

Katerina Kermeli



From baselines to deep reductions

Improving the modeling of industrial energy demand

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From baselines to deep reductions
Improving the modeling of industrial energy demand

Van baselines naar diepe reducties
Verbetering van de modellering van de industriële energievraag

(met een samenvatting in het Nederlands)

Proefschrift

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to *Yro*

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1 Introduction

1.1 Climate change and the role of industry

Global climate warming is underway for several decades increasing approximately at 0.2°C per decade. Compared to the pre-industrial period, 1850-1900, the global mean surface temperature (GMST) increased in 2006-2015 by 0.87°C (IPCC, 2018). Evidence on the human impact on climate change has grown, and it is now considered extremely likely that more than half of the temperature increase is attributed to the release of greenhouse gas (GHG) emissions from human activities and other anthropogenic forcings (i.e. aerosol release and land use change) (IPCC, 2014a). Driven predominantly by population and economic growth, anthropogenic GHGs have drastically increased and are now higher than ever before. The atmospheric concentration of CO_2 has climbed from the pre-industrial level of 280 parts per million (ppm) (IPCC, 2014a) to 408 ppm in 2018 (WMO, 2019).

In 2017, global anthropogenic GHG emissions reached 50 Gtonnes of carbon dioxide equivalent ($CO_{2\text{-eq}}$) (WRI, 2021), 85% higher than in 1970 (WMO, 2019). Carbon dioxide (CO_2) is the most important GHG (37 Gtonnes in 2017). The CO_2 emissions released from fuel combustion and industrial processes accounted in 2017 for about 66% of total GHG release and CO_2 from Land-Use Change and Forestry (LUCF) for 5%. The next most important GHGs are methane (CH_4) with 17%, nitrous oxide (N_2O) with 6% and F-gases with 2% of total GHG emissions in 2017 (WRI, 2021).

The industrial sector is responsible for the largest share of CO_2 released into the atmosphere. In 2018, industrial activities were responsible for 43%[1] (14.4 Gtonnes) of global CO_2 emissions from fuel combustion, of which 54% came from burning fuels and 46% indirectly from power consumption (IEA, 2020a). Except from being a major CO_2 emitter, the industrial sector is also the major energy consumer. In 2018, it accounted for 40% of global final energy consumption (see Figure 1-1).

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[1] It does not include energy producing industries (e.g. oil refineries and coal mining) and process CO_2 emissions. In 2017, industrial process emissions amounted to approximately 1.5 Gtonnes of CO_2 (WRI, 2021).

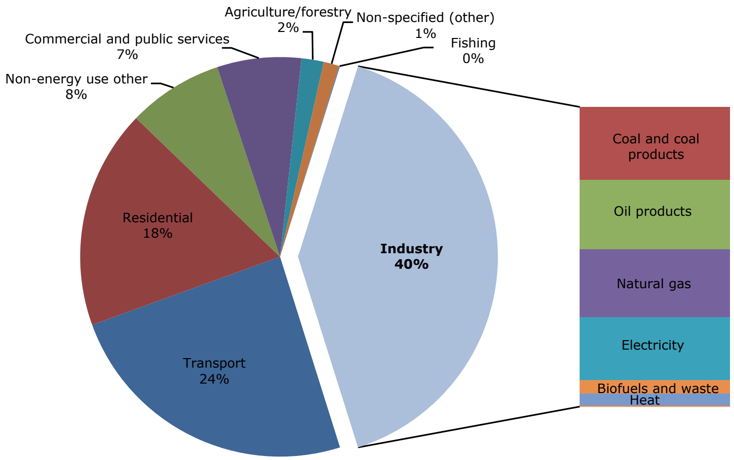

Figure 1-1 Total global final energy use per activity sector and per energy source in 2018 (IEA, 2020b)

In 2018, 200 EJ[2] of final energy was consumed by industries, where fossil fuel consumption accounted for more than 70% (IEA, 2020b). In 1980, final energy consumption was 135 EJ while in 1971 it was 120 EJ (IEA, 2016b). The manufacturing processes used to produce the bulk materials and industrial goods are energy intensive and hence represent the largest contribution to industrial energy use. Over half of the industrial energy use and emissions are for material production, see e.g. Worrell and Rosales Carreon (2017). Although past technological developments have greatly improved energy efficiency – e.g., the average energy intensity for steelmaking dropped 60% from 50 GJ/tonne in 1960 to 21 GJ/tonne today (World Steel, 2017a) – absolute energy consumption has drastically increased, due to increasing industrial activity.

Population and economic growth have increased the demand for materials consumed in various sectors of our economy (see Figure 1-2). The demand for steel, used largely by the transport and the building sectors, has experienced an annual increase of 2.5% in the period 1980-2019 (World Steel, 1978-2020). In the same period, the demand for cement, used mainly in construction activities, has experienced an annual increase of about 5% (USGS, 2017a; 2020a). Over half of materials are produced in China. In 2019, China was responsible for 53% of global steel production and 54% of global cement production. Since 2014, in China, cement production begun a decreasing trend at a 2%/yr rate (USGS, 2018a; 2019a; 2020a) while steel production continues to increase although at a slower pace, with 4%/year after 2014, compared to 14%/yr in the 2000-2014 period (World Steel, 2010; 2020).

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[2] It does include the energy use in coke ovens, blast furnaces, industry own use and energy use as feedstock.

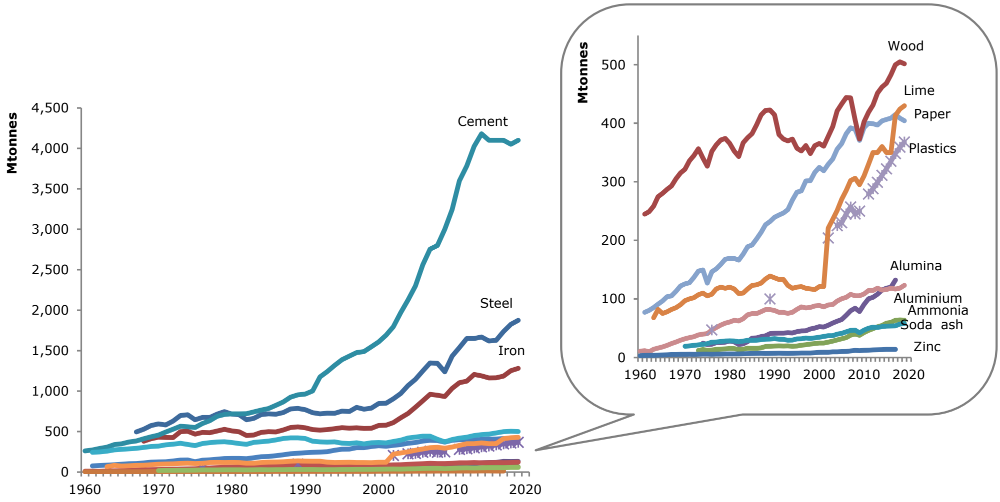

Figure 1-2 Global production of industrial products in the period 1960 to 2019. Sources: cement: USGS (2017a; 2018a; 2019a; 2020a); aluminium, alumina: IAI (2020); wood, paper: FAOSTAT (2020a; 2020b); ammonia: USGS (2017b; 2018b; 2019b; 2020b) zinc: USGS (2017c; 2020c); plastics: Plastics Europe (2016a, 2016b, 2019, 2020); pig iron, crude steel: World Steel (1978-2020)

It has been shown that material intensity (in kg/capita) increases at low and growing per capita GDPs and when a specific per capita GDP level is reached it saturates and even decreases (van Vuuren, 1999). At what point material use decouples from GDP is uncertain and can be country dependent, but it has been estimated to stabilize for cement in the range of 250-700 kg/capita (De Vries et al., 2006; Yellishetty and Mudd, 2014; Van Ruijven et al., 2016; Zhou et al., 2011). Müller et al. (2011), showed that the in-use iron stocks (iron contained in products currently in use such as cars, buildings etc.) experience strong growth during the industrialization and urbanization stages and saturate in the post-industrial era. Pauliuk et al., (2013) determined the saturation levels for in-use steel stocks to lie between 13±2 tonnes per capita in industrialized countries.

Since many countries with a large share of global population are still in the initial stages of their development, the need for bulk materials is expected to increase in the coming decades driving both industrial energy consumption and GHG emissions.

1.2 Meeting the climate challenge

In the IPCC's Fifth assessment report (AR5), the Intergovernmental Panel on Climate Change (IPCC) has concluded that if GHG emissions continue to increase at current rates and with no adequate mitigation measures in place, the global average temperature will most likely increase by more than 4°C compared to the temperature in the pre-industrial era (IPCC, 2014a). The associated risks will be many (e.g. flooding, extreme weathering, ocean acidification, species extinction) affecting both human and natural systems (IPCC, 2014b).

On December 2015, the Paris Agreement, an internationally binding agreement on climate change, was signed by countries under the United Nations Framework Convention on Climate Change (UNFCCC) with the main goal to limit global warming to well below 2°C compared to pre-industrial levels, pursue efforts for an even lower temperature increase of 1.5°C and prepare for the impacts of climate change (UNFCCC, 2015). In 2018, the IPCC Special report on global warming was published assessing the climate-related risks for natural and human systems originating from a mean temperature increase of 2°C and 1.5°C. Evidence indicates that to maintain most parts of the ecosystems global warming should be limited to 1.5° instead of 2°(IPCC, 2018).

The European Union (EU) has set its own strategies to combat climate change and has put in place GHG emission reduction targets that get steeper when moving towards the mid of the century. These are: i) the 2030 climate and energy framework (EC, 2019), and ii) the 2050 long-term strategy (EC, 2018a). According to which, by 2030, GHG emissions should be reduced by at least 40% (compared to 1990 levels) and the share of renewable energy should increase to 32% of total energy consumption. The energy efficiency should improve by 32.5% relative to the 2007 projections for the expected energy use in 2030 (EC, 2018b). More recently, the Climate Target Plan (EC, 2020b) proposes to increase the 2030 GHG emission reduction target to at least 55% (compared to 1990 levels). This could be achieved by increasing the renewables share to 38-40% with coal reducing by more than 70%, oil by 30% and natural gas by 25% (compared to 2015 levels). The energy efficiency should increase by at least 36% (compared to the 2007 Baseline scenario projections for 2030) (EC, 2020a). By 2050, the EU aims to achieve net-zero GHG emissions. For industry, this would require wide adoption of energy efficient technologies, and after 2035 the implementation of advanced technologies, Carbon Capture and Storage (CCS), switch to CO_2 emission free feedstocks and CO_2 emission free electric or H_2 driven processes (EC, 2018a).

China, which is responsible for a great sum of materials produced globally, has the 13th Five Year Plan (FYP) which sets goals for environmental improvements and emission reductions in the period 2016-2020 (CCCPC, 2015)[3]. Although the main priority was to achieve a sustainable economic growth, goals were also set for reducing the 2020 CO_2 emissions per unit of GDP by 18% compared to 2015 and the energy consumption by 15% (per unit of GDP) by 2020, compared to 2015. According to the plan, several technologies would have to be implemented across all sectors to reach the goals (CCCPC, 2015).

There is general scientific consensus that a combination of measures will need to be taken to achieve the targets (Fischedick et al., 2014):

- **Energy efficiency** (decreasing the energy use per unit of product/service)
- **Emission efficiency** (including e.g., fuel and feedstock switching to less CO_2 generating alternatives)

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[3] At the time of writing, the 14th Five Year Plan covering the period 2020-2025 had not yet been released.

- **CCS**
- **Material use efficiency** (e.g., higher yield/less scrap and defects, new product design),
- **Recycling and material re-use** (e.g., using retired products after decommissioning, using by-products from industries)
- **Product service efficiency** (e.g., car sharing, using cars and buildings for longer periods)
- **Demand reduction** (e.g., reduced demand for products and services)

Considering the industry's high energy use and its critical role in mitigating GHG emissions, many studies have assessed its energy and GHG intensity (Saygin et al., 2011; Worrell et al., 2009; Bühler et al., 2017; Griffin et al., 2017; Laurijssen, 2013; IEA, 2007, 2008, 2009, 2010, 2017b; 2017c). Furthermore, many models were developed to determine future projections and estimate the potentials for energy reduction and the role of CO_2 mitigating measures. Nevertheless, due to the large industry diversity (a large variety of industrial products and industrial processes used) and the many technologies and measures available, significant knowledge gaps and uncertainties still exist and certain areas need further investigation to support the climate policy initiatives.

The information usually reported in energy statistics can be too aggregated to allow for a good analysis of energy consumption and energy intensities. For example, the International Energy Agency (IEA) reports total final energy consumption per fuel and per country for the total non-metallics minerals sector and the total non-ferrous metal sector. Such aggregated data do not allow for an estimation of the current level of energy efficiency. Initiatives of industrial sectors such as the Global Cement and Concrete Association (GCCA) and the International Aluminium Institute (IAI) collect and report data, relevant for energy analysis. By combining statistics and collecting more sector and country level data a deeper analysis of the energy efficiency potentials and technologies that can offer the savings is permitted. ***In the first part of this thesis, we combine information and statistics to estimate the current and future significance of energy efficiency in industries of different regions (see Section 1.3).***

In addition, it is essential to investigate whether important insights from bottom-up case studies, such as current energy use of industrial sub-sectors per region, important technological options and technical potentials for energy efficiency improvement, are adequately captured in long-term energy models. Integrated Assessment Models (IAMs), a type of long-term energy modeling, are primarily used for assessing mitigation pathways and estimating the costs of mitigation and are being widely used in advising policy makers (Clarke et al., 2014). Although they are not very detailed, in recent years, some details have been added in modeling the energy end-use sectors (Krey, 2014). For good scenario projections, it is crucial, that the five main industries (iron and steel, cement, chemicals and petrochemicals, paper and aluminium) that emit the most GHG emissions are adequately represented in long-term energy models. *Therefore,* ***in the second part of this thesis, we address this topic by assessing key long-term***

energy models in the way they model the industrial sector, and by developing (simple) methods to better capture energy efficiency, material efficiency and material demand, improve the modeling of the industry sector (see Section 1.4).

1.3 Potentials for energy efficiency improvement in energy intensive industries

In 2018, the industrial sector consumed 164 EJ of final energy[4] (excl. feedstock use) of which 25% came from electricity and 75% from burning fuels (IEA, 2020a).

Figure 1-3 shows the energy consumption per industrial sub-sector. Excluding feedstock use, the most energy consuming industries, in descending order, are the iron and steel, the chemicals and petrochemicals, the non-metallic minerals, the food and tobacco, the pulp, paper and printing, the machinery and the non-ferrous metal industries. On a global level, the iron and steel industry contributes the most in the final energy consumption and CO_2 emissions (2.6 Gt in 2019). This is because, although steel is not as energy intensive as other industries, such as aluminium (72 GJ/tonne[5] primary aluminium (IAI, 2020) vs 21 GJ/tonne crude steel from iron ore (Keys et al., 2019)) the annual steel production is much higher.

The cement and the aluminium industries, which are part of the non-metallic minerals and the non-ferrous metals industries respectively, emit besides CO_2 from direct and indirect fuel combustion, also process emissions (emissions inherent to the process itself). The cement industry contributes another 1.6 $GtCO_2$[6] from emissions released during the calcination of limestone and the aluminium industry another 0.04 $GtCO_{2\text{-eq}}$[7] by releasing perfluorocarbons (PFCs) during aluminium smelting.

According to the IEA (2012), industrial productivity is expected to double or triple in the next 40 years. With the increasing demand for industrial goods, industrial energy use and GHGs are expected to increase further. The World Energy Outlook (WEO) estimates that if current trend continue, total final energy consumption[8] will increase by 29%; from 120 EJ in 2018 (IEA, 2020b) to 155 EJ in 2040 (IEA, 2020c).

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[4] In 2018, 36 EJ of fuels were consumed for non-energy use purposes in the entire industrial sector (in the chemical and petrochemicals industry alone 28 EJ were consumed for this purpose) (IEA, 2020a).

[5] Based on the world average energy use of 10.7 GJ/tonne for making alumina and 14.2 MWh/tonne for alumium smelting, and an alumina to aluminium ratio of 1.9 (IAI, 2020).

[6] For every tonne of clinker (intermediate product for cement making) produced, about 0.5 tonnes of $CO_{2\text{-eq}}$ process emissions are released (JRC/IPTS, 2010). In 2018, 4,050 Mtonnes of cement were produced (USGS, 2020a) were the global average clinker to cement ratio was 77% (GCCA, 2020).

[7] PFC gases, CF_4 and C_2F_6, have a global warming potential (GWP) of CO_2 of about 6,500 and 9,200 times the GWP of CO_2 respectively (IPCC, 2006). In 2018, for every tonne of primary aluminium produced 0.55 tonnes of $CO_{2\text{-eq}}$ process emissions were released (IAI, 2020).

[8] Total final energy consumption does not include the energy use in coke ovens, blast furnaces, industry own use, and energy use for non-energy purposes.

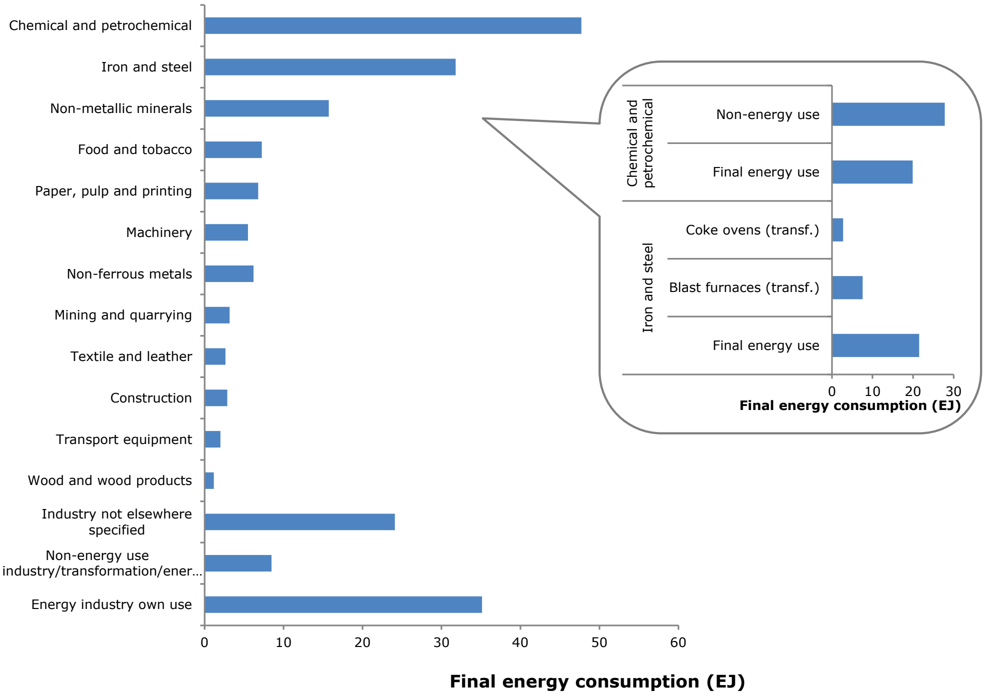

Figure 1-3 Energy consumption by industrial sectors in 2018 (IEA, 2020b)

Due to the different industry compositions and the level of technological development, the average energy intensities and the currently untapped technical potentials vary across regions/countries. In addition to determining the current technical potentials, it is important to also determine the future potentials in the different regions per sector. Industrial energy intensity has been decreasing as a result of autonomous energy efficiency (newer technologies tend to be more efficient than similar older ones), policy-induced energy efficiency improvement, and energy efficiency improvements due to structural changes (switching to the production of less energy intensive products). Consequently, it is interesting to identify to what extent the currently identified energy savings potentials will remain untapped in the future if current trends continue. This will give insight into what pace energy efficiency needs to be incorporated to reach the climate goals and to what industrial sectors each region should invest in energy efficiency or other measures (if energy efficiency is already achieved).

To accurately estimate the savings potentials and the required investments, each industry needs to be individually assessed so that specific industry characteristics and technologies are taken into account. The aluminium industry is an example of an energy intensive industry for which available information on regional energy use (the IEA provides data for the non-ferrous industry as a whole), technologies used per country and currently available energy efficiency technologies/measures are scarce. The IAI is a rich data source that provides useful information on production volumes, PFC emissions, and energy intensities but on a highly aggregated regional level. This makes it difficult to assess energy efficiency improvements with very few studies addressing it. Saygin et al. (2011) determined the technical energy savings potential from wide Best Practice Technology (BPT) adoption to 24% while it was found that about 80% of the energy savings can be realized in the manufacture of alumina (intermediate product for aluminum production). Although the aluminium production from alumina (aluminium smelting) is by far the most energy intensive step, the relatively low energy savings potential identified suggests that this process has already been significantly optimized (Green, 2007).

Gale and Freund (2001), Luo and Soria (2007), and more recently Moya et al. (2015) assessed energy efficient technologies for both the alumina and aluminium production but especially alumina production is not treated with detail. Consequently, determining the technical savings potentials in the main alumina and aluminum producing countries and the investment costs required per measure would allow to calculate the cost of emission abatement, a significant contribution in understanding the GHG potentials and associated costs.

With regard to the above knowledge gaps, the objective of the first part of this thesis is to answer the following research question:

What are the global and regional, current, and future potentials for energy savings in the industrial sector when considering the wide adoption of currently available energy saving measures? In Chapters 2 and 3 we answer this research question by:

i) analyzing the current energy use of six industrial sub-sectors in ten regions and determining, with the help of available information on current Best Practice Technology (BPT) and Best Available Technology (BAT) potentials and recycling rates, the energy consumption in the period 2008 to 2050 under a low energy demand scenario; and by

ii) analyzing the current industrial energy use for primary aluminium production covering all main steps (alumina refining, anode production and aluminium smelting) and identifying a variety of energy efficiency measures to determine the current and future energy savings and GHG abatement potentials per process for 11 primary aluminium producing and 7 alumina producing countries.

1.4 Capturing key industrial characteristics in long-term energy models for improved modeling results

To make long-term scenarios for energy development and GHG emissions and their impact on climate change, IAMs are commonly used. These models have, within a single modeling framework, a representation of the most relevant components for climate change (e.g., land, agriculture, energy, economy, atmosphere) and by assessing their interactions construct mitigation pathways to 2050 and beyond (Clarke et al., 2014). Their main objective is to deliver to policy makers an outlook of different climate futures when a variety of climate policies are in place and when not (Weyant, 2017).

The value of integrated model results has been widely recognized by policy makers and these have therefore been used in many global studies such as the UNEP Third Global Environment

Outlook (GEO-3) (Stehfest et al., 2014), the Global Energy Assessment (GEA) (GEA, 2012), and in compiling Chapter 6 of the IPCC fifth assessment report where about 1,200 model scenarios were used to create the different transformation pathways (Clarke et al., 2014; IIASA, 2014).

To cut emissions, transformation efforts are needed for both the energy demand and the energy supply systems (Clarke et al., 2014). However, although the energy supply sector is represented with a high degree of detail in IAMs, the energy demand sector and especially the industrial sector is represented in a rather stylized manner (Sugiyama et al., 2014; Clarke et al., 2014). This is primarily because the industrial sector is a highly diverse end-use sector, using different production processes to manufacture a variety of primary and secondary traded products making it difficult to incorporate in IAMs. However, total emissions coming from industry are larger than either the transportation or the buildings sector. Five industries, steel, cement, plastics, paper and aluminium are the dominant sources of industrial CO_2 emissions, these industries should thereby be properly represented by integrated models (Allwood et al., 2010).

Industry representation
Although so far, many model comparison studies have been conducted focusing on the way the energy system and the land use systems are modelled in IAMs (Van der Zwaan et al., 2013; Kriegler et al., 2014; Calvin et al., 2012; Rosen and Guenther, 2015; Girod et al., 2013; Calvin et al., 2013), few studies have compared how specifically the industrial sector is treated in integrated models. In the study by Zhang et al. (2015) it was evaluated how certain factors, such as the co-benefits of energy use and climate policies are modelled in integrated, bottom-up and top-down models for the Chinese industrial sector. In a recent study by Pauliuk et al. (2017), five IAMs were compared in detail with regard to the way material flows, stocks and recycling are modelled.

Projections of industrial energy use and GHG emissions are highly dependent on the data and methods used and the models structure and main assumptions made. This is reflected in the Fifth Assessment report where scenarios for the 21st century show a wide range of industry sector emissions (Fischedick et al., 2014). Consequently, there is limited understanding of why the industrial projections between models vary so widely, augmented also by the limited available documentation of industrial modules in IAMs.

Energy and material efficiency
Industrial energy efficiency is not being adequately represented in IAMs where in many cases "no-regret" energy efficiency measures are ignored although they do exist (Ackerman et al., 2009; Xu et al., 2010; Sathaye et al., 2010; Rosen and Guenther, 2015; Rosen, 2015). This is a crucial detail as energy efficiency has been recognized as one of the key ways to achieve an energy transition (IEA, 2017) if not the first policy option (Rosen and Guenther, 2010). Several detailed case studies have estimated the potentials for industrial energy efficiency from wide adoption of BATs to up to 25% (Schäfer, 2005; Allwood et al., 2010; UNIDO, 2011; Saygin et al., 2011b; Gutowski et al., 2013).

Material efficiency is another key measure that is not adequately represented in integrated models. Because IAMs in general treat the industry sector in an aggregated way, they do not provide information on material flows, material efficiency and price induced material substitution on a sub-sectoral level (Clarke et al., 2014), ignoring in most cases material cycles and recycling (Pauliuk et al., 2017). Material efficiency improvements can take place in many forms (Allwood et al., 2011; Worrell et al., 2016) such as material efficiency in production processes by improving and by re-using old materials, and in product designs by light weighing of consumer goods (e.g., cars, planes) and by substituting materials (e.g. substituting Portland clinker with Blast furnace slag cement).

To develop industry specific policies, it is necessary to make good estimates of the energy and GHG reduction potentials and associated costs and understand the role material demand and resource availability can play on energy use and GHGs. How accurate this information will be depends on how well the adoption of energy efficiency is represented in IAMs. In addition, improved modeling of material flows will give better estimates for the potentials for material efficiency and possible reductions in demand (Fischedick et al., 2014). The main underlying challenge is to capture all important dynamics within the industrial sub-sectors while at the same time keeping the data load at the desired detail level for IAMs.

Material demand
To project future bulk material demand, most studies relate material flows (i.e. annual consumption and production) to economic drivers and find patterns that are projected into the future (van Vuuren et al., 1999; de Vries, 2001; Crompton, 2000; Hidalgo et al., 2005; Neelis and Patel, 2006; Corsten, 2009, Zhou et al., 2013; van Ruijven et al., 2016). It has however been argued (Müller et al. 2007; Pauliuk et al., 2013; 2017) that the material in-use stocks (i.e., the materials contained in products that are in-use in a given year, such as the steel and cement in buildings and the steel and aluminium in cars) are better suited indicators of the services that materials provide in an economy than the material consumption.

Understanding and capturing the drivers of material demand and its saturation level is of crucial importance for long-term projections as it directly affects baseline energy use and GHGs. Ideally, demand would be coupled to insights in development of material needs for the main activity sectors (e.g., for steel it would be the construction, automotive and machinery sectors) in both developing and industrialized countries. Understanding key material flows will give insights on future demand and production levels and the volumes of generated material scrap. For some industries where recycling is important, such as the steel and aluminium industries, scrap availability is an essential parameter as it will define the recycling rates.

The objective of the second part of this thesis is to answer the following research question:

What is the representation of the industrial sector in long-term energy models and what impact does the inclusion of key industrial characteristics have on model projections? *We answer this research question in Chapters 4, 5 and 6 by:*

i) identifying the structure and main assumptions of widely used IAMs and comparing them to model output to understand the industry sector representation and sources of variations on model outcomes while also taking a closer look at the cement industry representation;

ii) collecting the data and developing a set of guidelines for including the cement industry in the less detailed long-term energy models. Incorporating in the IMAGE, IAM model, a method that accounts for 1) retrofitting with energy efficient technologies/measures and 2) clinker substitution with supplementary materials (the availability of which is linked to the activity of the industry that generates them) and assessing the impact on the original model results; and by

iii) adopting a different approach for forecasting steel demand in the IMAGE model which is based on a stock-based approach instead of a flow-based approach that is commonly used by long-term models, to estimate the steel demand in 26 regions in the period 2008-2100 and assess the impact on the original model results.

The IMAGE model

IMAGE is an integrated assessment model (IAM) operated by PBL (Planbureau voor de Leefomgeving), the Netherlands Environmental Assessment Agency and used to assess sustainability issues such as climate change and the impact of various climate policies by simulating the interactions between the human and the earth system (see Figure 1-4). It has a geographical resolution of 26 regions. A detailed description of the latest version of the IMAGE model and its different modules can be found in Stehfest et al. (2014) and online (PBL, 2014).

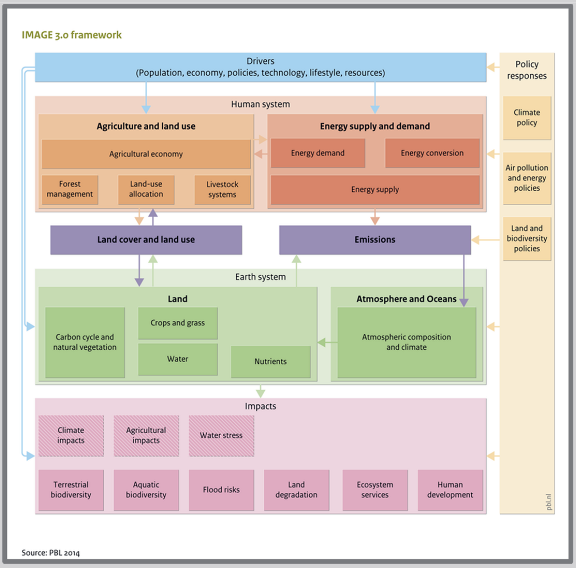
IMAGE 3.0 framework

Source: PBL 2014

Figure 1-4 IMAGE 3.0 framework (PBL, 2014)

The industrial sector in IMAGE

The energy demand module, TIMER, calculates the energy use for five end-use sectors: industry, transport, residential, services and other sectors (Stehfest et al., 2014). Detailed modules have only two of the most energy intensive industries: i) the cement and ii) the iron and steel industries.

The level of activity in the steel and cement industries is measured in physical units (i.e. tonnes of product). The demand for materials (apparent consumption) is approximated as a function of GDP per capita (van Ruijven et al., 2016). The trade of materials is also accounted for (production slowly shifts to the countries with the lower production costs) for both materials, however cement trade is limited. The steel and cement production in each region, after trade, is satisfied using a mix of production technologies derived from a multinomial logit model that basically assigns the higher market shares to the technologies with the lower production costs (van Ruijven et al., 2016). For each technology there is a specific energy intensity that slowly declines over time (autonomous energy efficiency improvement).

For example, for the cement industry, four production technologies are considered for new plant capacities; efficient, standard and two with CCS. Material efficiency in the form of clinker substitution is also accounted for, although exogenously. In the steel industry eight production routes are included that utilize a combination of technologies (e.g. blast furnace plus basic oxygen furnace). In addition, the scrap availability needed to assess recycling options is also modeled using material flow analysis (MFA) that calculates the steel scrap generated in the different stages of steel life (Neelis and Patel, 2006). Energy efficient production technologies and CCS are also included. For both industries fuel substitution is possible based on fuel prices but constrained by technological options (e.g. EAFs use electricity).

For more details on the TIMER module, see van Ruijven et al. (2016) and Neelis and Patel (2006).

1.5 Scope and outline of the thesis

This thesis focus is twofold. The first objective is to assess the impact the wide implementation of energy efficiency measures can have on industrial energy consumption. Currently available technologies are primarily assessed. The second objective is to assess the industrial representation in long-term energy models and identify key areas for improvement. The overall research question is:

To what degree can energy efficiency improvement decrease industrial energy demand and are key industry characteristics and mitigation measures sufficiently captured in long-term energy models?

There are two research sub-questions:

> *1. What are the global and regional, current, and future potentials for energy savings in the industrial sector when considering the wide adoption of currently available energy saving measures?*
>
> *2. What is the representation of the industrial sector in long-term energy models and what impact does the inclusion of key industrial characteristics have on model projections?*

The sub-questions are answered in the following chapters. Table 1-1 gives an overview of the different chapters and lists the main elements addressed in each chapter.

Table 1-1 Overview of thesis chapters and coverage of elements influencing industrial energy demand.

	Chapter	Energy efficiency	Material efficiency	Material demand	Industry representation in IAMs
Part 1	2. Energy efficiency improvement potentials and a low energy demand scenario for the global industrial sector	✓	✓		
	3. Energy efficiency improvement and GHG abatement in the global production of primary aluminium	✓		✓	
Part 2	4. Comparing projections of industrial energy demand and greenhouse gas emissions in long-term energy models				✓
	5. The scope for better industry representation in long-term energy models: modeling the cement industry	✓	✓	✓	✓
	6. Improving material projections in IAMs: the use of a stock-based versus a flow-based approach for the iron and steel industry			✓	✓

The thesis starts with **Chapter 2**, where we estimate the future industrial energy use and energy savings potentials of six industrial sub-sectors in ten world regions under two energy demand scenarios: (1) a reference scenario that represents a continuation of business-as-usual trends and (2) a low energy demand scenario that considers wide implementation of energy efficiency improvements. We built the reference scenario based on the IEA World Energy Outlook (WEO) and the low energy demand scenario based on the energy savings potentials estimated from the wide implementation of BATs and BPTs and increased recycling.

Chapter 3 focuses on the primary aluminium industry as a case study where we estimate the current and future potentials for energy savings and GHG abatement. This analysis identifies 22 currently available energy efficiency measures and constructs cost supply curves to determine the potentials for the two main processes in primary aluminium production, alumina refining and aluminium smelting. Our analysis quantifies the global potentials but also distinguishes the potentials per producing country. As the location of alumina refining and aluminium smelting plants is not the same, we distinguish the energy and GHG savings for the six main alumina producing and the eleven main aluminium producing countries. To determine the potentials, different country characteristics such as bauxite quality, processes used, and energy prices are considered.

The second part of this thesis starts with **Chapter 4**, which compares the industrial energy consumption and GHG emission projections of several IAMs. To understand result deviations, we compare input information and structural assumptions used. To better understand differences in projections we also examine how the energy demand of one specific industrial sub-sector, the cement industry, is represented in these models.

Chapter 5 examines the current representation of the cement industry in IAMs and identifies key areas for improvement. We then investigate the scope of adding bottom-up details in long-term IAMs by adding more detailed information to a single model, IMAGE. The focus is placed in two areas: 1) retrofitting with energy efficiency measures and ii) reducing the clinker content in cements. To account for retrofitting, cost-supply curves are constructed for each region. To account for the reduction of clinker content in cement a method that takes into account Supplementary Cement Materials (SCMs) availability based on the activity of the steel industry and power generation from coal is developed and incorporated into the model. We are particularly interested in understanding the impact of including key industry specific characteristics and industry interconnections on modeling results. In addition, we have constructed a set of guidelines for modeling the cement industry that could be adopted by the less detailed models that would like to improve industry representation.

Material demand is the first decisive variable that needs to be determined when making estimations of future energy consumptions and GHG emissions of any industrial sector. In **Chapter 6**, we investigate how the steel demand is modeled across main long-term models and examine whether demand projections differ when instead of a flow-based approach (based on observations of past developments on steel consumption) a stock-based approach (based on observations of past steel accumulation within economies) is used. We do this by using the insights from steel stock build-up and saturation levels from one specific Material Flow

Analysis (MFA) (Pauliuk et al., 2103a) to create a simple modeling approach to forecast steel demand in the IMAGE IAM model.

Finally, in **Chapter 7**, the thesis ends with the overall summary and the main conclusions.

Part 1:

Potentials for energy efficiency improvement in energy intensive industries

2 Energy efficiency improvement potentials and a low energy demand scenario for the global industrial sector[9]

Abstract

The adoption of energy efficiency measures can significantly reduce industrial energy use. This study estimates the future industrial energy consumption under two energy demand scenarios: (1) a reference scenario that follows business as usual trends; and (2) a low energy demand scenario that takes into account the implementation of energy efficiency improvement measures. These scenarios cover energy demand in the period 2009-2050 for ten world regions. The reference scenario is based on the International Energy Agency (IEA) World Energy Outlook (WEO) (2011 edition) up to 2035 and is extrapolated by Gross Domestic Product (GDP) projections for the period 2035-2050. According to the reference scenario, the industrial energy use will increase from 105 EJ in 2009 to 185 EJ in 2050 (excluding fuel use as a feedstock). It is estimated that with the adoption of energy efficient technologies and increased recycling, the growth in industrial energy use in 2050 can be limited to 140 EJ; an annual energy use increase of 0.7% compared to the 2009 case. The 2050 industrial energy use in the low energy demand scenario is estimated to be 24% lower than the 2050 energy use in the reference scenario. The results of this study highlight the importance of industrial energy efficiency by providing insights of the energy savings potentials in different regions of the world.

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[9] Based on Kermeli, K. W. Graus, and E. Worrell. (2014). Energy efficiency improvement potentials and a low energy demand scenario for the global industrial sector. *Energy Efficiency*, 7(6), 987-1011.

2.1 Introduction

During 1990-2009, the industrial energy use[10] worldwide increased from 83 EJ to 105 EJ, an increase of 26% (IEA, 2011a). In the past decades, the adoption of energy efficiency measures has reduced industrial energy intensity; however, increased energy demand due to increased industrial production has offset most energy gains from improved efficiency. With industrial productivity expected to double or triple in the following 40 years, industrial energy use and the associated greenhouse gas (GHG) emissions are expected to grow drastically (IEA, 2012). Currently, industrial activities are responsible for about a third of global energy use and 40% of emitted greenhouse gases (IEA, 2009a). The International Energy Agency (IEA), in the 2012 Energy Technology Perspectives (ETP), estimates that under the 6ºC Scenario (6DS) which is based on the continuation of current trends, industrial energy use will rise from 126 EJ[11] in 2009 to about 245-270 EJ in 2050 (including energy used as a feedstock) (IEA, 2012).

Improved energy efficiency can limit industrial greenhouse gas emissions as it results in decreased fossil fuel energy consumption. Energy efficiency is considered one of the most cost-effective ways of reducing greenhouse gas emissions (Ryan and Campbell, 2012), and one of the most important ways to mitigate climate change. The goal of this study is to estimate the energy savings potential and as a result, the energy use of the global industrial sector for the period 2009-2050 under a low energy demand scenario. This study is based on a number of scenarios prepared for UBA (2010) and for the Greenpeace EREC Energy [r]evolution scenario study (Graus and Kermeli, 2012).

This paper starts with a methodology description (Section 2.2), where the reference scenario and the technical potentials per industrial sub-sector are presented. Section 2.3 presents the results of this study and then follows a discussion of uncertainties (Section 2.4) and the conclusion (Section 2.5).

2.2 Methodology

This section describes the reference scenario and the methodology used for the development of the low energy demand scenario for the global industrial sector. In the reference scenario, the industrial energy demand follows current trends where no major changes take place in the production and consumption of end-use products. In the low energy demand scenario, the industrial energy demand is equal to the energy use in the reference scenario minus the identified technical energy savings potential. The reference scenario is described in section 2.2.1. A description of the approach used for the identification of the technical potentials in the major industrial sub-sectors is presented in section 2.2.2.

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[10] In this study, unless otherwise mentioned, industrial energy use also includes the energy use in coke ovens and blast furnaces that is reported in IEA statistics under the transformation processes and under the industry own use, and excludes the energy use in refineries and as a feedstock. The energy use in coke ovens and blast furnaces reported under the transformation processes represents the transformation losses for producing coke oven coke, coke oven gas, blast furnace gas and other recovered gases while the energy use in coke ovens and blast furnaces reported under the industry own use represents the primary and secondary energy use used for supporting the industrial activity i.e. energy use for heating, pumping and other purposes (IEA, 2004; IEA, 2011b).

[11] In 2009, the worldwide industrial energy use was 105 EJ excluding feedstock use and 126 EJ including feedstock use (IEA, 2011a).

2.2.1 Reference scenario

The reference scenario considers that the overall industrial energy use per different world region is equal to the energy use reported by the World Energy Outlook (WEO)[12] of the International Energy Agency (IEA, 2011c), with the addition of the energy use in coke ovens and blast furnaces which was estimated based on future steel production.

According to the WEO (2011 edition), under the Current Policies scenario in which no major energy efficiency improvements are expected, global industrial energy use will grow from 95 EJ in 2009 to 155 EJ in 2035 (excluding energy used in coke ovens and blast furnaces). The WEO 2011 Current Policies Scenario is broadly in accordance with the 6º Scenario (6DS) from IEA ETP (IEA, 2012), and runs from 2009-2035. For the period 2035-2050, the WEO scenario is extended by assumptions regarding Gross Domestic Product (GDP) and energy intensity developments. GDP assumptions for the period 2035-2050 are based on assessments on global GDP growth rates (DLR personal communication, 2012), where the GDP growth in all regions is expected to slow gradually over the next decades, following the trends in the period 2009-2035. Table 2-1 shows the regional economic growth development. In the reference scenario, global GDP will increase from 70.8 trillion US$ in 2009 to 245.5 trillion US$ in 2050 (in 2011 dollars, PPP); an increase of 247%. During the same period, population will increase from 6.8 billion in 2009 to 9.3 billion by 2050, an increase of 37%.

The WEO energy forecast does not take into account the energy used in coke ovens and blast furnaces (about 9% of overall industrial energy use in 2009 (IEA, 2011b)). To also account for it, we assume that in the 2009-2050 period, the energy use in coke ovens and blast furnaces will increase at the same rate as steel production in the primary steel making route. According to the IEA ETP, by 2050 steel production will increase by about 55% (IEA, 2012).

Table 2-1 GDP development projections (average annual growth rates) (2009-2035: IEA (2011c) and 2035-2050: DLR personal communication (2012))

	2009-2020	**2020-2035**	**2035-2050**	**2009-2050**
OECD Americas[1]	2.7%	2.3%	1.2%	2.0%
OECD Asia Oceania[1]	2.4%	1.4%	0.5%	1.3%
OECD Europe[1]	2.1%	1.8%	1.0%	1.6%
Transition Economies[1]	4.2%	3.2%	1.9%	3.0%
India	7.6%	5.8%	3.1%	5.3%
China	8.2%	4.2%	2.7%	4.7%
Other non-OECD Asia	5.2%	3.2%	2.6%	3.5%
Latin America	4.0%	2.8%	2.2%	2.9%
Middle East	4.3%	3.7%	2.8%	3.5%
Africa	4.5%	4.4%	4.2%	4.4%
World	4.2%	3.2%	2.2%	3.1%

[1] Projections on GDP growth are taken from WEO (IEA, 2011c). It should be noted though, that latest information on GDP reveals a weaker growth especially for developed countries. The level of the annual GDP growth rates affects the results of this study however, as in this study the reference scenario is based on the WEO energy forecast, we use the same GDP projections as WEO. If the recession continues or GDP growth rates don't increase soon this may lead to lower industrial energy use in the developed countries.

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[12] The WEO energy data does not include the energy used in coke ovens and blast furnaces.

This study looks only at the final energy demand, hereon referred to as energy demand, in the industrial sector in ten world regions. The ten world regions are the same with the ones used in the WEO 2011 edition (IEA, 2011c): OECD Europe, OECD Americas, OECD Asia Oceania, Transition Economies, China, India, Other non-OECD Asia, Latin America, Africa and Middle East. The final energy demand represents the actual energy used by the end users for the manufacture of the different products. The energy demand scenarios focus only on energy-related fuel, power and heat use. This means that feedstock consumption in industries is excluded from this analysis.

The future increase in industrial energy consumption, as a result of economic growth, will depend on the development of the economy's energy intensity; which in this study is defined as the final energy use per unit of gross domestic product. The energy intensity in an economy tends to decrease over time. Figure 2-1 shows the industrial energy intensity decrease per region in GJ/GDP. Improvements in energy intensity range between 0.9 to 3.2% per year, with the world average being 1.7% per year. This can be a result of several factors such as:

- *Autonomous energy efficiency improvement*, which occurs due to technological developments. Each new generation of capital goods is likely to be more energy efficient than the previous one;
- *Policy-induced energy efficiency improvement* as a result of which economic actors change their behavior and invest in more energy efficient technologies or improve energy management; and
- *Structural changes* that can have a downward or upward effect on the economy's energy intensity. An example of a downward effect is a shift in the economy away from energy-intensive industrial activities to service-related activities. Also, there can be demand saturation in certain sectors or countries.

In this research, autonomous and policy-induced energy efficiency improvements fall under our definition of energy efficiency improvements. Energy efficiency improvement is defined as the decrease in the specific energy consumption per product (gigajoules per tonne of crude steel, megawatt hours per tonne of aluminium, etc.).

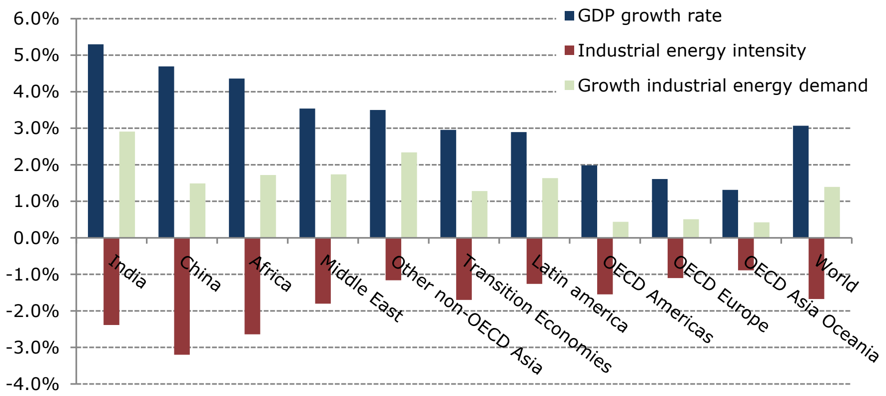

Figure 2-1 Annual growth rates of industrial energy demand, GDP and industrial energy intensity, in % per year in period 2009-2050 in the reference scenario

Figure 2-1 shows that industrial energy demand is projected to mostly increase in India and the Other non-OECD Asia (2.9%/year and 2.3%/year), followed by Africa (1.7%/year), Middle East (1.7%/year), Latin America (1.6%/year), and China (1.5%/year). Although the GDP growth in China is the second highest (4.7%/year), the growth in industrial energy demand is moderate. Energy demand increase is lowest in OECD Asia Oceania, OECD Americas and OECD Europe (between 0.4%/year and 0.5%/year), due to lower GDP growth rates, in combination with moderate energy intensity decrease.

Under the reference scenario, we assume that energy efficiency in each industrial sub-sector improves annually by 0.5%. This 0.5% autonomous energy efficiency improvement takes also into account the decrease of energy use due to structural changes within the industrial sub-sector; for example the shift from producing steel with the primary steel making route to producing steel from steel scrap. When calculating the potential for energy efficiency improvement, the energy efficiency that already occurs is the reference scenario is subtracted from the total potential in order to calculate the remaining potential relative to the reference scenario. Autonomous energy efficiency improvement is taken into consideration for all industrial sub-sectors. In the case of the non-metallics sub-sector we only deviate in the way we estimate the future energy savings potential (see the non-metallics paragraph in section 2.2.2 for more details).

The level of the autonomous energy efficiency improvement, equal to 0.5%, is based on available information in ETP for the 4DS scenarios on a sectoral level and on available historical trends. IEA (2012) shows that the annual autonomous energy efficiency improvement in the iron and steel, cement and primary aluminium industry under the 4°C Scenario is about 0.7%, 0.5-0.6% and 0.4-0.5%, respectively. The reference scenario is based on the WEO Current Policies scenario which is broadly in accordance with the 6°C scenario of the IEA ETP for which information on the level of the autonomous energy efficiency improvement is not available. As the 6°C scenario only takes into account a smaller range of energy efficiency improving measures than the 4°C, the included autonomous energy efficiency improvement in the 6°C is lower than in the 4°C.

In addition, historical energy use trends for the iron and steel, cement, primary aluminium and pulp and paper industrial sub-sectors indicate that in the past years, the energy use has experienced an annual decrease of about 0.4-0.5% for the iron and steel, primary aluminium and pulp and paper industries and 1.3% for the cement industry (see Table 2-2).

Table 2-2 Annual historical decrease in energy use in the iron and steel, cement, primary aluminium and pulp and paper industries

	Iron & steel	Cement	Aluminium smelting	Alumina refining	Pulp & paper
Period	1990-2009	1990-2009	1990-2009	1998-2012	1990-2009
Annual decrease in energy use	0.5%[1]	1.3%[2]	0.4%[3]	0.4%[4]	0.5%[5]

[1] Estimated based on production data from Worldsteel (2000, 2011) and energy use data from IEA (2011a).

[2] Estimated based on energy use data for clinker and cement making, and clinker to cement ratios reported in WBCSD/CSI (2012). An important part of the reduction in energy use was due to the reduction of clinker content in cement (76% in 2009 instead of 83% in 1990). For the same period fuel use and electricity use decreased annually by 0.9% and 0.5%, respectively.

[3] Based on reported energy use for aluminium smelting (IAI, 2013b).

[4] Based on reported energy use for alumina refining (IAI, 2013b) for the 1998-2012 period. China did not report data before 1998, and as China is one of the largest and most energy intensive alumina producers the world average energy use for alumina refining reported by IAI prior to 1998 is low.

[5] Estimated based on production data from FAOSTAT (2013) and energy use data from IEA (2011a).

This study estimates that worldwide industrial energy demand is expected to grow by 76%, from 105 EJ in 2009 to 185 EJ in 2050. As can be seen in Figure 2-2, energy demand in Chinese industries is expected to be substantial in 2050 and amount to 61 EJ; responsible for 33% of worldwide industrial energy demand.

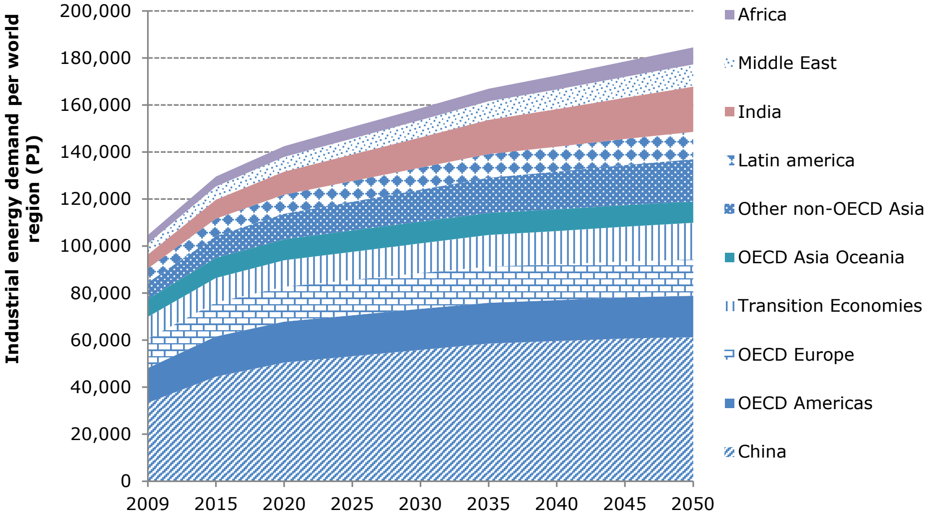

Figure 2-2 Industrial energy use per region in the reference scenario (for 2009 based on IEA 2011a)

The regional energy demand in 2050 for every industrial sub-sector is determined by multiplying the 2009 energy use with the regional increase in the overall industrial energy use. Therefore, it is assumed that the 2050 industrial structure remains the same with 2009. Figure 2-3 shows the breakdown of global industrial final energy demand by main industrial sub-sector in 2009 and in the reference 2050 and the low energy demand 2050 scenarios.

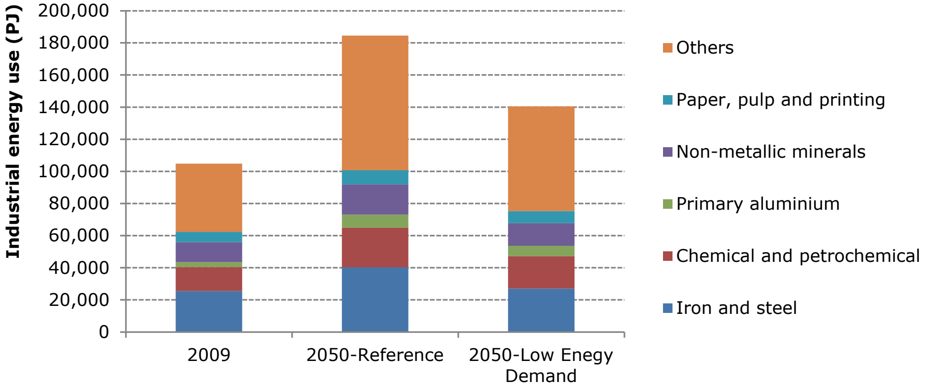

Figure 2-3 Breakdown of final energy consumption in 2009 and 2050 (for 2009 based on IEA 2011a)

The most energy consuming sub-sectors are chemicals and petrochemicals, iron and steel, pulp, paper and printing, non-metallic minerals, and non-ferrous metals. Together these sub-sectors consume 61% of industrial energy demand and are responsible for about 78% of industrial CO_2

emissions (IEA, 2012). For the above industrial sub-sectors, we look at implementing energy efficiency measures. The regional energy savings potentials for the iron and steel, primary aluminium and cement industries, are based on specific energy consumption data in physical units (MJ/tonne crude steel, MJ/tonne aluminium etc.), while for the chemicals and petrochemicals, pulp, paper and printing and the others industrial sub-sectors the potentials are based on global estimates.

2.2.2 Low energy demand scenario

This section discusses the assumptions for the potentials for energy efficiency improvements used for the low energy demand scenario. The section is structured by discussing potentials for the most energy consuming industrial sub-sectors, starting with iron and steel and followed by the non-metallic minerals, chemicals and petrochemicals, primary aluminium, pulp, paper and printing, and the others industrial sub-sectors. The energy efficiency potentials are based on literature studies and own calculations and take into account the implementation of best available technologies (BAT); and when there is not enough available information for this study, best practice technologies (BPT). Also, where possible, recycling is taken into account as a measure for improving energy efficiency.

BPT refers to the most advanced technology currently in operation at an industrial scale (IEA, 2012). By definition, BPT is economically viable. BAT is in general more technologically advanced than BPT; however, their implementation in a large industrial scale may not always be technologically or economically viable (IEA, 2009b).

The impact of the rebound effect (see Wei, 2010; Sorrell et al., 2009; Nadel, 2012; Saunders, 2013) on the energy savings potential is not taken into account in this study. According to the rebound effect, the gains from the implementation of energy efficiency measures are reduced by increased consumption and expenditures. For example, when an industry installs an energy efficient technology, its competitiveness can increase (due to the lower production costs) which can lead to high product demand that will result in a higher than before energy consumption. The actual effect of the rebound effect is not however clear, and therefore not taken into consideration in this study.

Ageing industrial equipment is de-commissioned and replaced by new equipment, which due to ongoing innovations in process technology, are most likely more energy efficient (de Beer 1998). In this study, it is assumed that within the 40-year timespan, all old plants will be replaced by new more efficient ones. This is based on the average plant lifetime of the various industrial sub-sectors that ranges between 30 and 50 years. Exceptions are the basic oxygen furnaces (BOFs), electric arc furnaces (EAFs), coke ovens, metals-based durables and the food and glass industries that appear to have a higher lifetime (EIA, 1999 as found in Worrell and Biermans, 2005). It is observed however, that the age of equipment is not the determining factor for de-commissioning old and inefficient equipment (Worrell and Biermans, 2005; Lempert et al., 2002). In order to achieve the energy savings appeared in this study, old plants will have to be replaced with new ones.

Iron and steel

The iron and steel industry consists of integrated steel mills that produce pig iron from raw materials (iron ore and coke) in blast furnaces and steel in BOFs or open hearth furnaces (OHFs), and secondary steel mills that produce steel from scrap steel, pig iron, or direct reduced iron (DRI) using EAFs.

Figure 2-4 shows the share of steel production per region by production process (Worldsteel, 2011). In 2009, basic oxygen furnaces accounted for 71% of worldwide steel production, while electric arc furnaces accounted for about 28%. Open hearth furnaces, an older and less efficient technology than basic oxygen furnaces, are only used on a large scale in the region "Transition Economies".

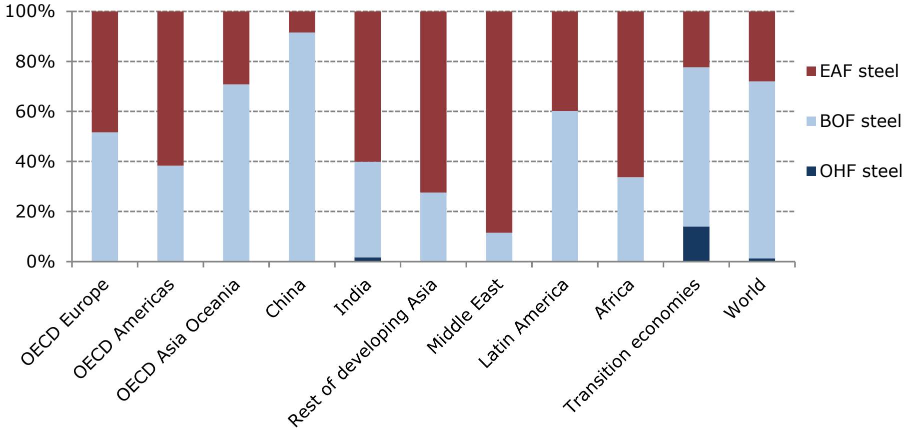

Figure 2-4 Steel production per region by technology in 2009 (based on Worldsteel 2011)

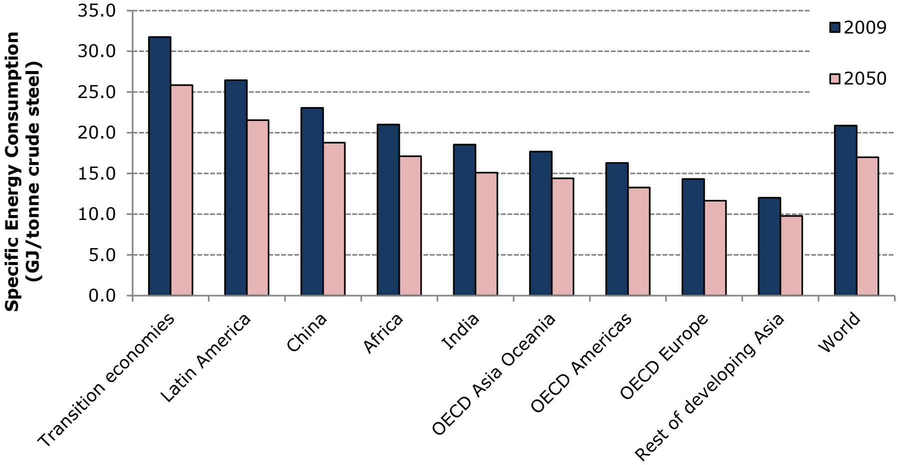

Figure 2-5 Specific energy consumption (GJ/tonne crude steel) in the reference scenario (based on IEA 2011a and Worldsteel 2011)

Figure 2-5 shows the specific energy consumption for iron and steel production by region in 2009 and in the reference scenario in 2050. The specific energy consumption in 2050 is based on a yearly energy efficiency improvement in the reference scenario of 0.5% (see Section 2.2.1 for more details regarding the energy efficiency improvement in the reference scenario). The 2009 specific energy consumption is based on the final energy demand of the iron and steel sub-sector and the fuel use in coke ovens and blast furnaces in IEA Energy Balances 2009, and the crude steel production by region in 2009 reported in the Steel Statistical Yearbook 2011. The Middle East is not included in the figure due to data unreliability. The world average energy use in 2009 was 20.9 GJ/tonne crude steel, including coke ovens and blast furnaces. OECD Americas, OECD Europe and Rest of developing Asia have the lowest energy consumption per tonne of steel. This is primarily due to their low levels of iron production. In 2009, the ratio of iron to steel production in these regions was 41%, 49% and 40%, respectively. In 2050, the energy use per tonne of crude steel is estimated to drop to 17.0 GJ/tonne crude steel due to the 0.5% autonomous energy efficiency improvement occurring in the reference scenario.

Table 2-3 shows the typical, current best practice and the theoretical minimum energy requirements for steel production. The typical energy use is considered to be representative of the current average energy use in steel manufacturing. Energy use for steel making from scrap is significantly less energy intensive than steel produced in the primary steel production route. Increasing the share of recycled steel production along with the adoption of more energy efficient technologies can reduce the overall energy use for steel production.

Table 2-3 Specific final energy consumption for iron and steel production [EIPPCB (2013), IEA (2007) and Worrell et al. (1999) for typical energy use, Worrell et al. (2008b) for current best practice and de Beer et al. (1998) and Fruehan et. al (2000) for theoretical and practical minimum]

Process	Specific Final Energy Consumption (GJ/tonne crude steel)		
	Typical energy use	Current best practice	Theoretical minimum (practical minimum)
Primary steel production in basic oxygen furnace (BOF) including energy use in blast furnaces (BF), coke ovens and sinter plants[1]	17-18[2]	14.5[3]	6.6 (N/A)
Steel production in electric arc furnace (EAF) with scrap as input	2.4	2.4	1.3 (1.6)
Direct reduction process (using natural gas), including energy use in EAFs and sinter plants[1]	17.0	16.1[4]	N/A
Smelting reduction process	N/A	16.9	N/A
Continuous casting	0.1	0.1	N/A
Hot rolling	2.0-2.4	1.8	0.03 (0.9)
Cold rolling and finishing	1.8	1.5	0.02 (0.02)
Thin slab/near net shape casting	N/A	0.2	N/A

[1] In IEA statistics, the energy requirements for pelletizing are usually not accounted for in the iron and steel making category (iron pellets are mainly produced at the mines) (IEA, 2007) and therefore the energy use in pellet plants is not included.

[2] According to the EIPPCB (2013) the typical energy use in the traditional BF route is 17-18 GJ/tonne liquid iron (including coke oven, sinter plant and blast furnace). About 1.14 tonnes of metallics are needed per tonne of liquid steel produced and 1.03 tonnes of liquid steel are used for the production of crude steel (Neelis and Patel, 2006). We assume that about 15% of the metallics input is scrap, based on a reported 3-25% share of scrap input in BOFs (Neelis and Patel, 2006).

[3] The best practice energy use for the BOF primary route is based on 90% pig iron and 10% scrap (Worrell et al., 2008b).

[4] The best practice energy use for the DRI-EAF route is based on 60% DRI and 40% scrap (Worrell et al., 2008b).

Besides using BPT, increasing the share of steel produced from steel scrap will reduce the overall energy intensity. In 2009, 440 Mtonnes of scrap were consumed in steel manufacturing (BIR, 2012). In the same year, the ratio of scrap consumption in the total crude steel production was 36% (BIR, 2012; Worldsteel, 2011). Scrap is mainly used in EAFs and BOFs, while a significant amount of scrap is also used in the production of cast iron (IEA, 2007). In 2009, 342 Mt of steel were produced in EAFs. About 80% of metallics consumed in EAFs is scrap (Neelis and Patel, 2006; IEA, 2007) and about 1.1 tonnes of metallics are required to produce 1 tonne of crude steel (Neelis and Patel, 2006). This means that in 2009, about 300 Mtonnes of scrap were consumed in EAFs; 68% of overall scrap consumption.

The steel recycling potential depends on scrap availability. Neelis and Patel (2006) estimate the potential for the share of scrap in total steel production to reach about 45% in 2050; about 40% of steel will be produced from scrap. Thus, we assume that the amount of recycled steel in total steel production can be increased from 36% in 2009 to 45% in 2050, 68% of which will be consumed in EAFs, same as in 2009. Therefore, about 25% of steel in 2050 will be produced from scrap in EAFs and 15% of steel will be produced from scrap in BOFs. By taking into account the amount of iron used in EAFs (about 20% of metallics input), the amount of steel produced in EAFs from scrap and other metallics in 2050 is estimated at 31%.

Additional energy savings can be achieved in steel casting with the use of continuous or thin slab/near net shape casting. Thin slab casting systems can reduce the need for hot rolling, as steel products are cast closer to the shape of the final product (Worrell et al., 2008b).

For the estimation of the energy saving potentials with the adoption of BPT and increased recycling, it is very crucial to determine the share of the different steel producing routes. The assumptions to our estimations are the following:

- 31% of steel is produced from scrap and iron in EAF furnaces, and the remaining 69% is produced from iron ore and scrap in blast furnaces. We assume that in 2050, 80% of the metallics input in EAFs is scrap, 13% direct reduced iron and 7% pig iron, similar to 2001 (Neelis and Patel, 2006). To be consistent with the best practice energy values used (see Table 2-3) we assume that when DRI is used in EAFs the mix used is 60% DRI and 40% scrap;
- 69% of steel is produced in blast furnace - BOF combination from iron ore (78%) and scrap (22%);
- the OHF-route has been phased out;
- 66% (70% of the 94% of the hot rolled steel share in 2009 (Worldsteel, 2011)) of the steel production is cast in thin slab casting systems;
- 28% (30% of the 94% of the hot rolled steel share in 2009 (Worldsteel, 2011)) of the steel production is hot-rolled; and
- 25% of steel is also cold-rolled (same as in 2009 (based on the European average share (Eurofer, 2011))).

Together with the best practice values for steel production in Table 2-3 this leads to a specific final energy consumption for iron and steel production of 11.8 GJ/tonne crude steel by 2050 in all regions[13]. This means that increased recycling and the adoption of best practice technologies, has the potential to reduce the 2050 energy use in the iron and steel industry by 31% from 17.0 GJ/tonne crude steel, as world average, to 11.8 GJ/tonne crude steel.

Non-metallic minerals

Non-metallic minerals include cement, lime, glass, soda, ceramics, bricks and other materials. Since cement accounts for most of the energy use in the non-metallic minerals sub-sector (IEA,

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[13] For the Middle East we assume no energy savings since data for specific energy consumption is low.

2007; IEA, 2009a), in this section, we specifically address the potential for energy efficiency improvements in the cement industry.

The main processes in cement manufacturing are raw material preparation, clinker production (limestone calcination) and cement grinding. Clinker production is the most energy intensive step (Worrell and Galitsky, 2008). Clinker is produced by burning a mixture of mainly limestone, silicon oxides, aluminium oxides and iron oxides in a kiln. Based on the moisture content of raw materials, clinker production can take place in a wet, dry, semi-dry or semi-wet kiln. The dry process has lower energy requirements due to lower evaporation needs.

The adoption of more energy efficient technologies and the decrease of the clinker content in cement can significantly reduce the energy use in cement manufacturing (Worrell et al., 2013). In the following paragraphs the potentials are identified for fuel savings in clinker making, electricity savings in cement making and the fuel savings due to a lower clinker to cement ratio.

The thermal energy use for clinker production in the different world regions ranges between 3.1 and 6.1 GJ/tonne clinker (see Figure 2-6). In 2009, the average heat use for clinker production is estimated in this study at 3.7 GJ/tonne clinker. This is based on energy use and clinker to cement ratio data reported by the WBCSD/CSI (2012). For China, we use the information reported in Xu et al. (2012) as the WBCSD/CSI database has only a small coverage (around 15%) for this region. Cement production data were taken from USGS (2002, 2007, 2012).

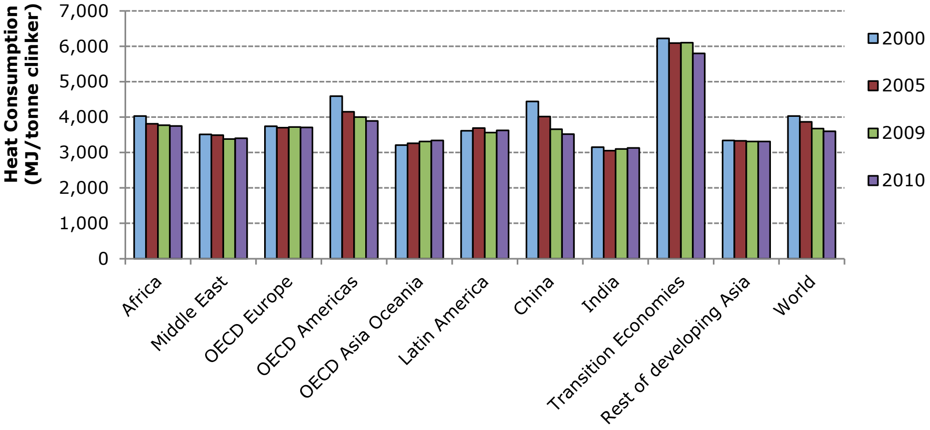

Figure 2-6 Heat requirements for limestone calcination in the different world regions (based on WBCSD/CSI, 2012, Xu et al., 2012 and USGS, 2002, 2007, and 2012)

Dry kilns equipped with a precalciner and several preheater stages (5 to 6 stages) are currently considered best available technology and can have under optimal conditions a fuel consumption of about 2.9-3.3 GJ/tonne clinker (EIPPCB, 2010). The theoretical minimum energy requirements are about 1.65-1.8 GJ/tonne (WBCSD/CSI-ECRA, 2009). The difference in energy use between typical kilns and the theoretical energy occurs due to heat losses; 0.2-1.0 GJ/tonne clinker are for drying raw materials with a 5% and 13% moisture content respectively, and the rest are thermal losses (WBCSD/CSI-ECRA, 2009). The theoretical value cannot be reached due to technical reasons (i.e. unavoidable heat losses through kiln surfaces) (IEA/WBCSD, 2009). The energy use in state-of-the-art dry kilns is not expected to significantly decrease in the future (IEA, 2009a). The current implementation of BAT can decrease the 2009 energy use from 3.7 GJ/tonne to 2.8 GJ/tonne. The reference scenario is based on the WEO Current Policies energy use forecast which is broadly in accordance with the IEA ETP 6DS scenario in which the 2050 heat use for clinker making is estimated at 3.7 GJ/tonne. We therefore estimate that in 2050 the energy savings potential in comparison to the reference scenario will be 24%.

In the cement industry, electricity is mainly used for the preparation of raw materials, fuels and additives and for cement grinding. Current state-of-the-art techniques use roller presses and vertical roller mills for grinding. The energy requirements will mainly depend on raw material hardness, moisture content and the type and amount of additives used. Figure 2-7 shows the electricity use for cement making in the different world regions. In 2009, the average electricity use is estimated at 101 kWh/tonne cement. This is based on the energy use data reported by the WBCSD/CSI (2012) for every world region and Xu et al. (2012) for China. Cement production data were taken from USGS (2002, 2007, 2012). The implementation of best practice technology can decrease the 2009 electricity use from 101 kWh/tonne to 90 kWh/tonne[14]; a decrease of 11%. The reference scenario in this study is constructed based on the WEO Current Policies scenario which is broadly in accordance with the 6DS which estimates an electricity use for cement making of 100 kWh/tonne in 2050. Thus, we estimate that the electricity savings potential in comparison to the reference scenario in 2050 to be 11%.

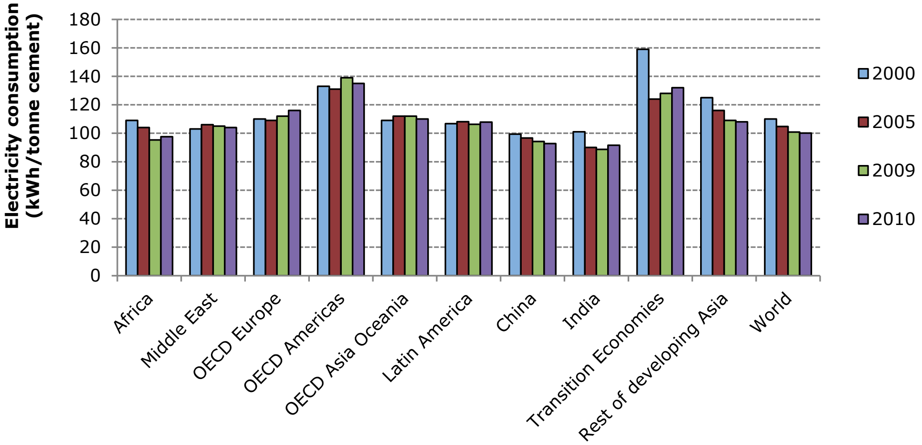

Figure 2-7 Electricity requirements for cement making in the different world regions (based on WBCSD/CSI 2012, Xu et al. 2012 and USGS 2002, 2007, 2012)

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[14] Best practice fuel and electricity use for cement making is based on Worrell et al. (2008b) for cement with 65% Blast Furnace Slag.

Additional energy savings can be obtained by reducing the clinker content in cement. Clinker can be substituted by industrial by-products such as coal fly ash, blast furnace slag or pozzolanic materials (e.g. volcanic material). The relative importance of additive use can be expressed by the clinker to cement ratio. Figure 2-8 shows the clinker content in cement per different world region. The 2009 average clinker to cement ratio is estimated at 70% and is based on data from WBCSD and Xu et al. (2012). We assume that in 2050 the clinker to cement ratio can drop to 65%. A similar ratio is used by the IEA (2012) in the 2ºC scenario (2DS). Decreasing the current clinker content by 7%, will reduce the heat use for clinker making from 2.0 GJ/tonne cement in 2009 (after BAT adoption) to 1.8 GJ/tonne cement; an additional decrease of 7% in heat use. The 6DS in IEA, which is broadly in accordance with the WEO Current Policies scenario used in the construction of the reference scenario in this study, estimates the 2050 clinker to cement ratio at 72-73%. Thus, in this study, we estimate that the energy savings potential in comparison to the reference scenario in 2050 is about 11%.

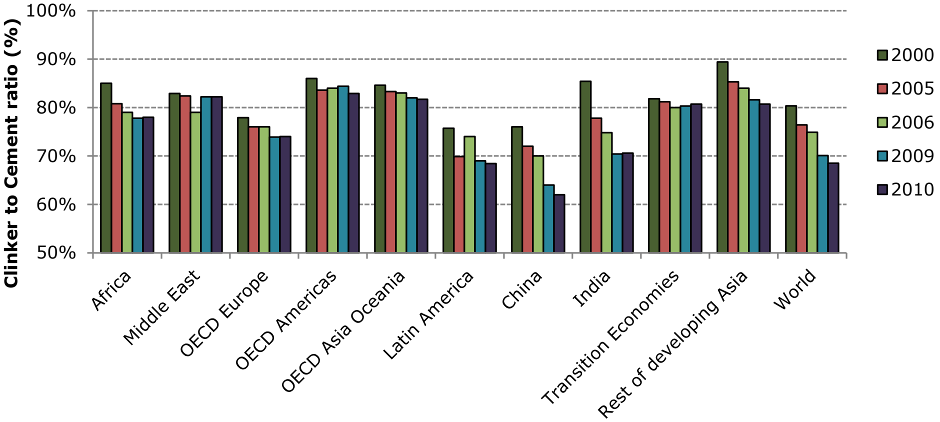

Figure 2-8 Clinker content in cement in the different world regions (based on WBCSD/CSI 2012, Xu et al. 2012 and USGS 2002, 2007, 2012)

In summary, we assume that the specific energy use for cement production can be reduced from 2.9 GJ/tonne to 2.1 GJ/tonne cement in 2050, reducing the specific energy use for cement making by 27%. We also assume that the potential for energy savings in the cement industry is representative for the total non-metallic minerals sub-sector. However, it should be noted that this is an oversimplification that can potentially lead to an underestimation of the energy savings potentials in the non-metallic minerals sub-sector. The manufacture of other non-metallic minerals such as lime, glass and ceramics is quite different than the manufacture of cement. Saygin et al. (2011a) estimates that wide BPT adoption can reduce the energy use for lime and glass making by 40% and 45%, respectively.

Chemicals and petrochemicals

The chemical and petrochemical industry is a major industrial energy consumer, responsible for about 16% of the 2009 industrial energy use (excl. feedstocks). Within this sub-sector, a large number of products are produced with about 75% being plastics (IEA, 2012). About 80% (excl. feedstock use) of the fuel consumption is for producing ethylene, propylene, methanol, ammonia, soda ash and for processing olefins (IEA, 2007). In this study, we look specifically at the potentials for improving the energy efficiency in the following key processes: steam cracking (used for the manufacture of olefins and aromatics), ammonia production, methanol production, chlorine production and soda ash production.

Steam cracking. According to the EIA (2009a), in the petrochemical industry, hydrocarbon feedstocks are used in steam cracking to produce olefins (ethylene, propylene) and aromatics (benzene, toluene and xylene). These products are further processed into polymers, solvents and resins. Steam cracking results in a big variety of products with varying energy intensities and accounts for about 20% of the final energy use (excl. feedstocks) in the chemical and petrochemical industry. The 2006 world average energy intensity (excl. feedstocks and electricity) is estimated by Saygin et al. (2011b) at 16.9 GJ/tonne of High Value Chemicals (HVCs)[15]. With the wide implementation of best practice technology, the current energy efficiency could improve by 26%, reducing the energy intensity to 12.5 GJ/tonne HVCs. If the BAT is adopted, energy efficiency could be further improved by another 15% (Saygin et al., 2011a), which would represent an overall energy efficiency improvement of 37%.

Ammonia production. The manufacture of ammonia accounts for about 32% (excl. feedstock and electricity) of the energy consumed in the chemical and petrochemical industrial sub-sector (IEA, 2007). Ammonia is mainly used as a feedstock in fertilizer production. The world average energy use is estimated by Saygin et al. (2011b) at 20.9 GJ/tonne ammonia (excl. feedstock and electricity). Current best practice energy intensity for natural gas based-ammonia production is 10.9 GJ/tonne ammonia (excluding feedstock and electricity) while best practice fuel use for oil-based and coal-based ammonia production (mainly used in China and India) is estimated at 17.3 and 16.1 GJ/tonne, respectively (IEA, 2009a). If all countries were to adopt best practice technology, the current energy efficiency would improve by 50%.

Methanol production. Methanol is used as antifreeze, solvent and fuel. In 2004, methanol production was responsible for about 4% of the fuel use (excl. feedstocks) in the chemical and petrochemical industry (IEA, 2007). The majority of methanol production (80%) is natural gas-based with the remainder, mainly taking place in China, being coal-based (IEA, 2007). The world average energy use in methanol production is estimated at 10.9 GJ/tonne (excl. feedstock and electricity) (Saygin et al., 2011b). The current worldwide adoption of best practice technology, 8.5 GJ/tonne (excl. feedstock and electricity), would result in a 22% decrease of the energy use.

Chlorine production. Chlorine manufacture is the main electricity consuming process in the chemical and petrochemical industry, accounting for 13% of the sub-sector's electricity use

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[15] In the Saygin et al. (2011b) study, the chemicals included under HVCs are: ethylene, propylene, benzene, butadiene, acetylene and hydrogen (sold as a fuel). The chemicals not included are: toluene and xylene.

(Saygin et al., 2011b). For example, the membrane process, consumes about 2,600 kWh/tonne chlorine, and is already close to the most efficient technology considered feasible (IEA, 2008 and Sinton et al., 2002). At the moment however, the mercury process is still commonly used, with an energy-intensity of around 4,000-4,500 kWh/tonne chlorine. Worldwide the average energy intensity is around 3,600[16] kWh/tonne chlorine (IEA, 2008 and Sinton et al., 2002). This corresponds to a current energy savings potential of 28%, based on the application of membrane technology for all chlorine production.

Soda Ash production. Soda ash is mainly produced for use in the glass industry. There is the synthetic production route, where synthetic soda ash is manufactured from limestone and common salt through the ammonia-soda process and the natural production route (used in the U.S.) where soda ash is manufactured from natural ash deposits and soda recovered from lakes. The manufacture of soda ash is responsible for about 5% of the fuel use in the chemical and petrochemical industrial sub-sector (IEA, 2007). Energy use in the synthetic route ranges between 10.6 and 13.8 GJ/tonne in different countries, while the world average energy intensity is estimated at 10.9 GJ/tonne (excl. feedstock and electricity) (Saygin, 2011b). Best practice technology (synthetic route) requires 10 GJ/tonne of soda ash (IEA, 2009a) and its adoption would improve the current energy efficiency by 8%.

The current fuel saving potentials in the above key processes (responsible for about 60% of the fuel use in the chemical and petrochemical sub-sector) range between 8 and 50%. Based on the identified BPT saving potentials and the share of these processes in the overall fuel use, the average current fuel savings are estimated at 37%. For the remaining 40% of the fuel use, we make the conservative assumption that there is a similar potential to save energy. As some of the savings have already been adopted in the reference scenario due to the autonomous efficiency improvement (see Section 2.2.1) we estimate that by 2050 the energy efficiency can be improved by 23% additionally.

About 65% of electricity use in the chemical and petrochemical industries is consumed in motor systems (i.e. pumps, fans, compressors), 13% in the production of chlorine and sodium hydroxide, and 22% in other electrolytic and electric arc processes, and non-process related usages (i.e. lighting) (Saygin et al., 2011b). Energy efficiency in motor systems can be improved by 20-30% through the use of highly efficient motors and adjustable speed drives (Waide and Brunner, 2011), while in chlorine production energy efficiency can be improved by 28% with the use of membranes. For the remaining processes that use electricity, we assume that efficiency can be improved by another 25%. Overall, the electricity savings are estimated at about 25%. After excluding the 0.5% annual autonomous energy efficiency improvement already implemented under the reference scenario, there still remains the potential to further decrease the electricity use by 9%.

Primary aluminium

Aluminium can either be produced from bauxite ore (primary aluminium production) or scrap (secondary aluminium production) (Green, 2007). In primary aluminium production, bauxite

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[16] 3000 kWh/tonne in Japan, 3500 kWh/tonne in Western Europe and 4300 kWh/tonne in the United States.

ore is refined into alumina through the Bayer process, where crushed bauxite is dissolved into a mix of sodium hydroxide and sodium carbonate (digestion). Impurities are then removed and the solution is precipitated and then calcined in rotary or stationary kilns to produce alumina. In 2009, the energy use in the various world regions ranged between 9.6 and 22.3 GJ/tonne (see Table 2-4), while the world average energy use was 14.6 GJ/tonne alumina. In 2050, the energy use of alumina refining in the reference scenario is estimated to drop to 11.9 GJ/tonne due to the 0.5% autonomous energy efficiency improvement taking place in the reference scenario.

Table 2-4 Alumina production and energy use per region in 2009 [(USGS 2011b) for alumina production, (EAA 2010) for energy use in OECD Europe, (Trudeau et al. 2011) for energy intensity in India and (IAI 2013b) for energy use in the rest of the regions, IEA (2011a) for overall industrial energy use]

Region[1]	Alumina production (Mtonnes)	Specific energy consumption (GJ/tonne)	Overall energy consumption (PJ)	Share in energy consumption industry (%)
OECD Europe	5.4	11.4[2]	62	0.5%
OECD Americas	3.5	11.8	41	0.3%
OECD Asia Oceania	20.3	11.4	231	3.6%
Transition Economies	6.3	22.3[3]	141	1.7%
China	23.8	19.4	462	1.6%
India	3.7	14.4[4]	53	1.0%
Rest of developing Asia	0.0	-	-	-
Latin America	12.9	9.6	124	2.1%
Africa	0.5	17.0	9	0.3%
World	76.7	14.6	1,122	1.2%

[1] Middle East is not included due to the lack of data.

[2] The energy use for alumina refining in OECD Europe is estimated based on the fuel use reported in EAA (2010) for the EU27 and EFTA countries (10.4 GJ/tonne alumina) (USGS, 2011b). Electricity use comprises about 3-15% of the overall energy use (IAI, 2013a; Worrell et al., 2008b).

[3] In 2009, OECD Europe was responsible for 48% and the Transition Economies for 52% of alumina production in the Europe region (as defined by the IAI). For an energy use of 11.4 GJ/tonne in OECD Europe and an energy use of 17.1 GJ/tonne in Europe (IAI, 2013b) we estimate the energy use in Transition Economies at about 23 GJ/tonne.

[4] We assume that the energy use in 2009 is similar to the one in 2007.

The typical energy use for alumina production with the Bayer process is 12 GJ/tonne (Henrickson, 2010). China and Russia due to their poor-quality bauxite reserves have used alternative processes to produce alumina; the Combined Bayer-Sinter and the Sinter processes with typical energy consumptions of 26 and 38 GJ/tonne alumina, respectively (Li et al., 2008; Smith, 2009). Other processes that have been only recently widely used in China are the Floatation-Bayer and the Lime-Bayer processes (Gu and Wu, 2012). If China and Russia would use good quality bauxite and adopt the more energy efficient Bayer process, the energy consumption would significantly decrease. In 2009, the world average energy use for alumina refining, excluding China, is estimated at 12.5 GJ/tonne alumina. Energy efficient alumina refineries (Bayer process) can have an energy use of 8-11 GJ/tonne (Wischnewski, 2011; Worrell et al., 2008b; Henrickson, 2010), while the theoretical minimum energy requirement is 0.24 GJ/tonne (U.S. DOE-EERE, 2007).

The production of primary aluminium from alumina is the most energy intensive step in primary aluminium production. Aluminium is produced by passing a direct current through a bath with alumina dissolved in a molten cryolite electrode. In 2009, the electricity use in the various world regions ranged between 14.2 and 15.6 MWh/tonne aluminium[17] (see Table 2-5). Secondary aluminium production uses only 5% of the energy demand for primary production because it involves remelting of the metal instead of the electrochemical reduction process (Phylipsen, 2000). In 2009, the average electricity use was 14.6 MWh/tonne aluminium. In 2050, the energy use of aluminium smelting is estimated to drop to 11.9 MWh/tonne aluminium due to the 0.5% autonomous energy efficiency improvement occurring in the reference scenario.

Table 2-5 Primary aluminium production and energy use per region in 2009 [(USGS, 2011a) for primary aluminium production, (EAA, 2010) for energy use in OECD Europe, (IEA, 2012) for energy use in India and (IAI, 2013b) for energy use in the rest of the regions, (IEA, 2011a) for the overall industrial energy use]

Region	Primary aluminium production (Mtonnes)	Electrical power used (MWh/tonne)	Electricity consumption (TWh)	Share in electricity consumption industry (%)
OECD Europe	4.1	15.1	61	6%
OECD Americas	4.8	15.0	71	6%
OECD Asia Oceania	2.0	14.4	28	5%
Transition Economies	4.7	15.6	74	14%
China	12.9	14.2	183	9%
India	1.4	14.9	21	6%
Rest of developing Asia	0.3	14.7	4	1%
Latin America	1.9	15.5	30	9%
Africa	2.0	14.7	29	13%
Middle East	2.5	14.8	36	30%
World	36.9	14.6	538	8%

The theoretical minimum energy requirement for electrolysis is 6.0 MWh/tonne while current best practice is 13.5 MWh per tonne (IEA, 2009a). Sinton et al. (2002) estimates best practice electricity use for smelting to drop to 11 MWh/tonne by 2015. We assume that an 11 MWh/tonne energy use (including electricity use in auxiliary equipment) for the best practice technology can be reached in 2050.

In 2009, about 18 million tonnes of aluminium were produced from old scrap (GARC, 2009); representing one third of overall aluminium production. Recycling rates for building and transport applications range from 60-95% in various countries. By improving aluminium recycling, e.g. the aluminium recycling of aluminium cans, the recycling rates can be further increased. An increase of the recycling rate from 33% in 2009 to 40% in 2050 (based on IEA, 2009a) would decrease the share of primary aluminium production in the overall production

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[17] This is AC electricity use, also including electricity use in rectifiers for converting AC current to DC and electricity use in auxiliary equipment.

by 10%. This would save about 9.5% of the electricity consumption for aluminium production (assuming secondary aluminium uses 5% of the energy demand for primary production) and 10% of the energy consumption for alumina production as the demand for alumina will decrease.

In addition to the recycling of aluminium, the adoption of energy efficient technologies can reduce the energy use for aluminium smelting from 11.9 MWh/tonne in 2050 to 11.0 MWh/tonne aluminium; an energy savings potential of 8%. Also, the energy use for alumina refining can be reduced from 12.0 GJ/tonne in 2050 to 9.5 GJ/tonne alumina; an energy savings potential of about 21%.

Overall, combining the remaining energy savings potentials from increased recycling and the adoption of energy efficient technologies under the reference scenario in which autonomous energy efficiency has already been implemented, the world average saving potential for primary aluminium production (alumina refining and aluminium smelting) is estimated at 22%.

Pulp and Paper

The pulp and paper industry (including printing) is the fourth largest industrial energy consumer. In 2009, the pulp and paper industry consumed 6.3 EJ; approximately 6% of industrial energy use (IEA, 2011a). Unlike other industries, the pulp and paper industry is a major biomass consumer (~50% of energy use). Biomass consumption in the IEA dataset might be under-reported as in many cases it is included under the non-specified industries (IEA, 2009a).

Main energy consuming processes are chemical pulping, mechanical pulping, paper recycling and paper production. Most of the energy used is for heat purposes and about a quarter for power generation (IEA, 2009a). Integrated plants (pulp and paper mills) are more energy efficient than pulp mills due to improved waste heat recovery (IEA, 2012). According to Overgaag et al. (2009), the replacement of old plants with new energy efficient plants will have the greatest potential for energy efficiency improvement of about 20%. Some of the most promising energy saving technologies are black-liquor gasification, advanced drying technologies and high temperature and high-pressure black-liquor recovery boilers (IEA, 2009a).

Producing pulp from recovered paper will reduce the energy use by 10-13 GJ/tonne, depending on the type of paper and type of pulping substituted (IEA, 2009a). In 2010, the world paper recycling rate, defined as the ratio of the total recovered paper used to the global paper production, was 58% (CEPI, 2011). The highest ideal technical limit of recycling rate is estimated at 81% (CEPI, 2006); however, the practical limit may be lower (IEA, 2009a).

The energy savings potential from BAT adoption is estimated at 15% by the IEA (2012), while according to Saygin et al. (2011a), the adoption of BPT can decrease current energy use by 28%[18]. Here, to consider the energy efficiency from BPT adoption we take the average, 22%.

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[18] Although by definition the adoption of BAT would result into more energy savings than the BPT adoption, it is not clear why in the IEA study a lower energy savings potential than in Saygin et al. (2011a) is estimated.

Also, based on the IEA (2012), each 1% increase in the paper recycling rate in 2010 will result in about 0.05 EJ of energy savings. If the paper recycling rate can be raised from 58% in 2010 to 70% (average of the current global recycling rate and the upper technical limit of recycling rate), about 0.6 EJ of energy can be saved; that is an energy savings potential of 10%. We assume that such an increase in the recycling rate will translate into similar energy savings in 2050. This leads to an average energy savings potential from improved efficiency through BPT implementation and increased recycling of about 30%. When the autonomous energy efficiency improvement is taken into account there still remains a potential of 14% to decrease the energy use.

Other industrial sub-sectors

The energy use in the remaining industries, corresponding to between 41% and 46% of industrial energy demand in 2009 and 2050, respectively, is aggregated into the Other industrial sub-sectors (hereon Others). The energy use of this industrial sub-sector can decrease with the use of state-of-the-art processes and equipment, and increased material efficiency. For example, improving the efficiency of motor systems in industrial plants can reduce electricity use by 20-30% (Waide and Brunner, 2011) while a total site pinch analysis can result in average energy savings of 20-25% (Linhoff March, 2000).

If we assume that the energy use in the Others sub-sector can experience an analogous decrease with the energy use in the highly energy intensive industries (equal to the weighted average energy savings potential in the iron and steel, chemical and petrochemical, non-metallics, primary aluminium and pulp and paper industries), then fuel use can be reduced by 28% and electricity use by 18%. Estimating the energy savings potential in the Others sub-sector based on the energy savings potential in the high energy intensive industries may lead to underestimating the energy savings potential. This is because the Others sub-sector is mainly composed of Small and Medium sized Enterprises (SMEs), that although not very energy intensive, typically have a larger potential for energy efficiency improvement than the highly energy intensive industries (Saygin et al., 2010).

2050 technical potentials

The industrial energy use can be substantially reduced with the adoption of currently available energy efficient technologies and with increased recycling. Table 2-6 shows the resulting industrial energy savings potentials in comparison to the reference scenario per region in 2050. These are based on the technical potentials with the subtraction of the energy efficiency improvement already included in the reference scenario. In the reference scenario, a part of the energy efficiency improvements have already been implemented (autonomous and policy induced energy efficiency improvement). Details about the yearly energy efficiency improvement occurring under the reference scenario are discussed in Section 2.2.1.

Table 2-6 Reduction of energy use in comparison to the reference scenario per industrial sub-sector in 2050

World regions:	Iron and steel[1, 5]		Primary aluminium[2]		Chemicals & petrochemicals[3]		Non-metallic minerals[4]		Pulp, paper and printing[1]		Other industries	
	fuel	electricity	fuel	electricity	fuel	electricity	fuel	electricity	fuel	electricity	fuel	electricity
OECD Europe	0%[6]	0%[6]	9%	19%	23%	9%	34%	20%	14%	14%	13%	11%
OECD Americas	11%	11%	12%	19%			46%	35%			22%	14%
OECD Asia Oceania	18%	18%	8%	14%			33%	20%			20%	15%
China	37%	37%	46%	16%			22%	5%			31%	19%
Latin America	45%	45%	0%	19%			26%	15%			29%	24%
Africa	31%	31%	38%	17%			38%	6%			31%	15%
Middle East	-	-	0%	18%			34%	14%			22%	13%
Transition Economies	55%	55%	53%	23%			63%	30%			47%	30%
India	24%	24%	27%	19%			17%	0%			23%	19%
Rest of developing Asia	0%	0%	0%	17%			33%	17%			24%	9%
World[7]	33%	32%	30%	18%	23%	9%	29%	10%	14%	14%	26%	17%

[-] The energy savings potentials in steel making in Middle East were not estimated due to unreliable 2009 energy use data.

[1] The energy savings potentials are based on the wide implementation of BPT and increased recycling.

[2] The energy savings potentials are based on the wide implementation of BPT for alumina refining, BAT for aluminium smelting and increased recycling.

[3] The energy savings potentials are based on the wide implementation of BPT.

[4] The energy savings potentials are based on the wide implementation of BAT in the cement industry and increased clinker to cement ratio.

[5] The energy savings for steel making were estimated based on the overall energy use (fuel and electricity) in BPTs. Therefore, and due to the lack of data concerning the specific fuel and electricity use in BPTs, we have assumed that there is the same potential for fuel and electricity savings. In reality however, the energy savings potentials for fuel and electricity would be different.

[6] For an analysis dealing with the iron and steel industry in Europe, please see Pardo et al. 2012 and Fleiter et al. 2013. Pardo et al. (2012) estimate that with the adoption of BAT and innovative measures, the 2030 energy use in the European iron and steel industry could decrease by 10%. Fleiter et al. (2013) estimate that under a frozen efficiency scenario, the 2035 energy use for iron and steel manufacture in Germany can decrease by 11%.

[7] The world energy savings potentials are slightly different from the ones determined for every industrial sub-sector in previous paragraphs. This is because the share of the different regions on the overall energy use in 2050 is different from the one in 2009.

Worldwide, the energy savings potentials differ substantially per region. This is due to the different energy use under the reference scenario in each region. For example, in the case of the non-metallic minerals sub-sector, China and India appear to have a lower energy savings potential than OECD Europe and OECD Americas. This is because the energy savings are only based on cement manufacture, in which, according to available information, China and India are characterized by some of the lowest clinker to cement ratios and a comparatively low heat and electricity usage in clinker and cement making (see Figure 2-6, Figure 2-7 and Figure 2-8), respectively. In 2009, the clinker to cement ratio was 62% for China, 74% for OECD Europe, while for OECD Americas it was 83%. The energy savings potential in OECD Americas might be overestimated, since in the United States, SCMs are primarily used in concrete plants and not in cement plants (see also Table 2-10).

2.3 Results

According to the low energy demand scenario, industrial energy use (including coke ovens and blast furnaces and excluding feedstocks) is 24% lower than the energy use in the reference scenario; 140 EJ instead of 185 EJ in 2050 (see Figure 2-9). In comparison to the reference level in 2050, energy demand is 27% lower for fuel use (89 EJ instead of 122 EJ in 2050) and 18% lower (51 EJ instead of 62 EJ) for electricity use.

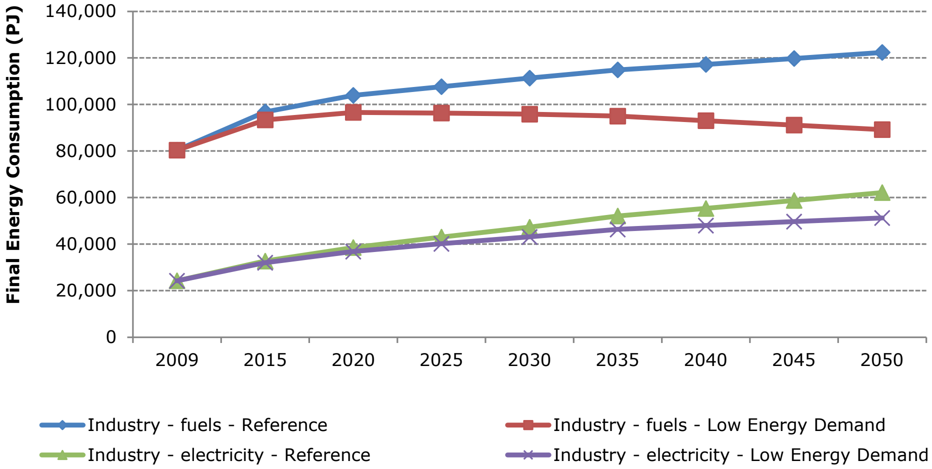

Figure 2-9 Global final industrial energy use in the period 2009-2050

Table 2-7 shows the energy demand per industrial sub-sector in 2005 and 2050 under the reference and the low energy demand scenarios, and the potentials for energy savings. The energy use in the reference scenario increased from 105 EJ in 2009 to 185 EJ in 2050; an increase of 76%. In the low energy demand scenario, the energy use increases annually by 0.7% from 2009 to 2050. That is from 105 EJ in 2009 to 140 EJ in 2050, equivalent to an increase of 33%.

Table 2-7 Energy use in the reference and low energy demand scenarios per industrial sub-sector

	Reference Scenarios (EJ)				Low Energy Demand Scenario (EJ)					
Industrial sub-sectors:	2009		2050		Energy demand in 2050		Energy saved in 2050		Savings share (%)	
	fuel	electricity	fuel	electricity	fuel	electricity	fuel	electricity	fuel	electricity
Iron and steel	22	3	32	8	21	6	11	3	32	11
Primary aluminium	1	2	3	6	2	5	1	1	2	9
Chemicals & petrochemicals	11	4	16	8	13	8	4	1	11	15
Non-metallic minerals	11	2	15	4	10	4	4	0	13	7
Pulp and paper	5	2	6	3	5	2	1	0	3	5
Other industries	30	12	51	33	38	27	13	6	39	53
Total	80	24	122	62	89	51	33	11	100	100

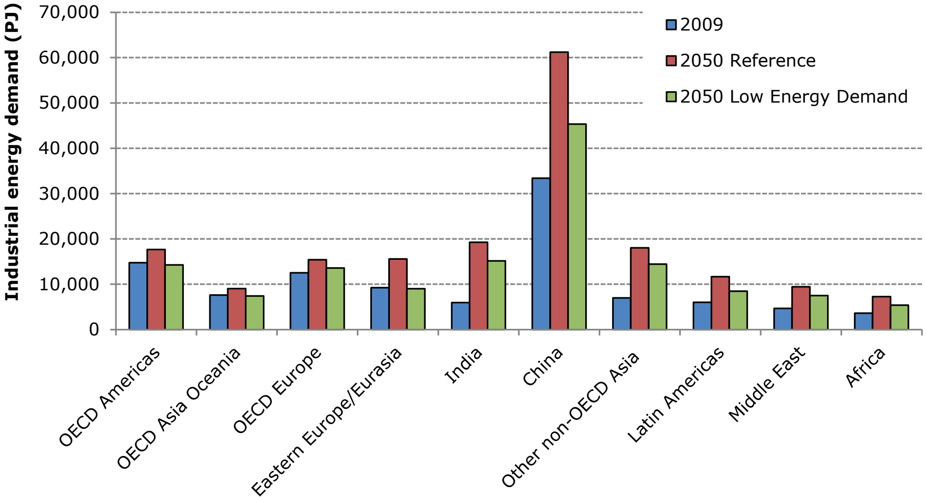

Figure 2-10 Industrial energy use in the different scenarios per world region

Most of the energy savings will take place in the Others industrial sub-sector, and then follow the iron and steel and the chemical and petrochemical industrial sub-sectors. Figure 2-10 shows the final energy demand in the different world regions under the different scenarios.

Figure 2-11 shows that industrial energy demand in the low energy demand scenario is projected to mostly increase in India and the Other non-OECD Asia (2.3%/year and 1.8%/year), followed by Middle East (1.2%/year), Africa (1.0%/year), Latin America (0.8%/year), and China (0.7%/year). Energy demand increase is lowest in OECD Asia Oceania, OECD Americas and OECD Europe (between -0.1%/year and 0.2%/year). The global industrial energy demand growth under the low energy demand scenario is 0.7% instead of 1.4% in the reference scenario (see Figure 2-1).

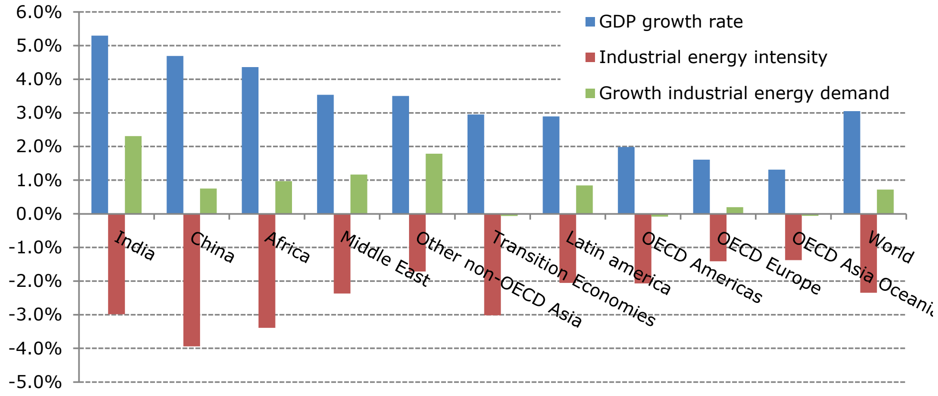

Figure 2-11 Annual growth rates of industrial energy demand, GDP and industrial energy intensity, in % per year in period 2009-2050 in the low energy demand scenario

Comparison to the IEA ETP and other studies

In this research study, the potential for decreasing the industrial final energy use was estimated at 44 EJ, which is 24% of the energy use in the reference scenario in 2050. In the IEA ETP study (2012) the industrial energy use (including feedstocks) is estimated to decrease by about 10% in the 4°C Scenario (4DS) and about 24% in the 2°C Scenario (2DS). IEA estimates that industrial energy use (incl. feedstocks) will decrease from 258 EJ in 2050 in the 6DS to about 230 in the 4DS and 195 in the 2DS. Table 2-8 gives a summary of the results of this study in comparison to the IEA ETP 2012 study.

Table 2-8 Comparison of the industrial energy use development in 2050 (in EJ)

	Current Study			IEA ETP 2012			
	2009 Ref. Scenario	2050 Ref. Scenario	2050 Low Energy Demand Scenario	IEA Ref. Scenario 2009	IEA 6°C Scenario 2050[1]	IEA 4°C Scenario 2050[1]	IEA 2°C Scenario 2050[1]
Total (excl. feedstocks)	105	185	140	105	N/A	N/A	N/A
Total (incl. feedstocks)	126	219[2]	175	126	245-270 (258)	225-240 (233)	190-200 (195)
Energy savings potential	-	-	-20%	-	-	-10%	-24%

[1] For each scenario, IEA estimates the energy use under two cases; the low demand case and the high demand case. In this Table, to facilitate the comparison, the average of the low and the high demand cases is also presented in the parenthesis.

[2] It is assumed that the 2050 feedstock use to the chemicals and petrochemicals energy use (incl. feedstocks) ratio remains the same as in 2009, 58%.

As can be seen in Table 2-8, this study estimates that under the reference scenario, industrial energy use will increase by 76% by 2050. IEA (2012) estimates a more significant increase of the industrial energy use under the 6DS[19] of about 95% and 115% under the low- and high-demand scenarios, respectively. The estimated 2050 energy use under the reference scenario in this study is 23 EJ lower than in the 6DS low-demand scenario estimated by IEA.

As seen in Table 2-8, the low energy demand scenario shows a higher potential for energy efficiency improvement than the IEA 4DS and a bit lower than the 2DS. The difference between the low energy demand scenario estimated in this study and the IEA 4DS can be partly explained with the more conservative estimations of current energy savings potentials the IEA makes for each industrial sub-sector when compared to this study (see Table 2-9). In addition, this study uses higher recycling rates than IEA for the estimation of the energy savings potentials. In the 2DS, the low energy demand is achieved by the wide adoption of BAT, improved material producing techniques, the adoption of innovative technologies and increased recycling. In addition, in the 2DS, Carbon Capture and Storage (CCS) is also implemented outweighing a fraction of the energy savings from improved energy efficiency (IEA, 2012). In this research, the 20% energy savings is achieved with the implementation of BPTs and BATs and increased recycling only.

The estimated, current, energy savings potentials from the wide implementation of BAT/BPT alone are broadly in agreement with the results of other studies (see Table 2-9). When making this comparison, note that the energy savings potentials among the different studies are estimated for different base years. In this study, the identified energy savings potential for alumina refining (35%) is lower than the potential estimated in other studies, as i) a higher energy use for BPT (9.5 GJ/tonne alumina) has been used and ii) the world average energy use

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[19] Similarly to the reference scenario in our study, the 6DS of IEA is based on the continuation of current trends.

for alumina refining in 2009 was 14.6 GJ/t while in 2007 (base year on the Saygin et al. (2011a) study) it was 15.5 GJ/t. The potential for energy savings for aluminium smelting is higher than in other studies as a future BAT energy use was used for the construction of the scenarios. For a current BAT of 13.5 MWh/tonne the current energy savings potential would be 7%. It should be noted that for the chemical and petrochemical industry the results are not easily comparable. Both IEA (2009a) and Saygin et al. (2011b) estimate the energy savings potentials for the entire chemical and petrochemical industry (including feedstocks) from BPT implementation while in this study the energy savings potentials are based on the wide implementation of BPT on current energy use that excludes feedstocks.

Table 2-9 Comparison of current energy savings potentials from BAT/BPT adoption

	Iron & steel industry	Primary aluminium industry		Chemicals and petrochemicals industry	Cement industry	Pulp & paper industry
		alumina refining	aluminium smelting			
current study	26% (BPT)	35% (BPT)	24% (BAT)[1]	37% (BPT)	22% (BAT)	22% (BPT)
IEA (2009a; 2012)	20% (BAT)	12% (BAT)		15% (BPT)[2]	20% (BAT)	15% (BAT)
Saygin et al. (2011a, b)	24% (BPT)	50% (BPT)	14% (BAT)	16% (BPT)[2]	24% (BPT)	28% (BPT)

[1] Estimated based on a future BAT energy use of 11 MWh/tonne aluminium.

[2] This is the potential for decreasing the overall energy use (including feedstocks) in the chemicals and petrochemicals industry.

2.4 Discussion of uncertainties

This research aims to investigate the future industrial energy use under a low energy demand scenario. A variety of different literature sources were used for the estimation of the energy saving opportunities in the most energy consuming industrial sub-sectors. For a number of sub-sectors, such as the iron and steel, cement and primary aluminium, the saving potentials are different for every region as they are based on the level of current energy use (megajoules per tonne product) in each region and the BAT or BPT energy use. For the chemical and petrochemical and the pulp and paper industrial sub-sectors the energy savings potentials are based on world average values and are therefore the same for every world region.

Table 2-10 presents the areas in which data improvement will strengthen the results and improve the estimations of a future low energy demand scenario in which current BPT and BAT implementation will limit the impact of material consumption.

Table 2-10 Major areas for data improvement per industrial sub-sector

Industrial sub-sectors	Major areas for data improvement
Iron and steel	• More accurate data on energy use in Middle East.
Non-metallic minerals	• The energy savings potential estimated for the cement industry is assumed to be representative of the entire non-metallic minerals sub-sector. Additional research is required to assess the energy savings potentials in the lime, glass and ceramic product manufacturing. • It is assumed that the clinker to cement ratio can be reduced from the current level in each region to 65%. However, in some countries cementitious substituting materials are mainly used in concrete plants, such as in the case of U.S. (Staudt 2009). Due to this, the energy savings from clinker substitution might be overestimated for some regions.
Chemicals and petrochemicals	• Global estimates were used for the calculation of the energy efficiency potentials. This results in the same energy saving percentages for every region. The use of regional data would result in a more accurate overview.
Primary aluminium	• The 2009 regional energy use for alumina refining and aluminium smelting was retrieved from available literature and statistics. The energy use in Transition Economies however, was estimated. • To achieve the energy savings potential in alumina refining, good quality bauxite needs to be used in all regions. As some of the major alumina producers, China and Russia, use low-quality bauxite, the energy savings might not be achieved.
Pulp and paper	• Regional savings potentials were based on global estimates. Using regional data would result in a more accurate picture of the regional saving potentials. • According to the IEA (2009a) biomass use might be under-reported. More accurate data would reduce the uncertainty of the results.
Others	• The energy savings potentials were based on the weighted energy savings potential of the above industrial sub-sectors. Further disaggregating the Others industrial sub-sector and looking into more detail in the possible energy savings potentials would be of major research value. In the study conducted by Saygin et al. (2011a), the Others industrial sub-sector as defined in this report, is further disaggregated and the current energy savings potentials of a number of manufacturing industries (copper, zinc, lime, glass, ceramics, textile, and food and beverages) are identified. The importance of energy efficiency improvements in the smaller industrial segments has been addressed and assessed by several studies (e.g. Worrell et al., 2008a; Worrell et al., 2010; Kermeli et al., 2011).

Future energy savings potentials

It can be difficult to quantify the future energy savings potentials. To do so, the future energy consumption prior to the energy efficiency improvements needs to be estimated. In this study, it is assumed that the autonomous energy efficiency improvement is equal to 0.5% per year (see Section 2.2.1), while we deviate for the non-metallics sub-sector (the energy savings potential is estimated based on the 2050 energy use in the cement industry; see the non-metallics section for more details). The annual autonomous energy efficiency improvement is based on available information in the 6DS and 4DS in the ETP. A different annual autonomous energy efficiency improvement would result in a different energy savings potential in 2050.

For an autonomous energy efficiency improvement of 0.25%, the energy use in 2050 in the low energy demand scenario will be 130 EJ; 29% lower than in the reference scenario, while if the autonomous energy efficiency improvement is increased to 0.75% the 2050 energy use in the low energy demand scenario will be about 152 EJ; 18% lower than the reference scenario. In Appendix 2A the energy savings potentials are shown under different autonomous energy efficiency improvements.

Increase in energy use per industrial sub-sector

In this study, the 2050 industrial energy use for every different industrial sub-sector is estimated based on the average increase in industrial energy use per region. Therefore, this approach does not take into consideration structural changes or product substitution (i.e. steel substitution with aluminium).

Future energy use in coke ovens and blast furnaces

The energy consumed in coke ovens and blast furnaces accounts for about 36% of the energy used in the iron and steel industry. The future energy consumption is based on the WEO Current Policies scenario in which the energy use in coke ovens and blast furnaces is not included. To account for the above energy use, we assume that it will grow at the same rate as steel production from the blast furnace route. IEA (2012) estimates that under the 6DS, steel production with the BF/BOF route will increase by 40% under the low demand scenario and by 70% under the high demand scenario. For this study we assume that by 2050 the energy use in coke ovens and blast furnaces will increase by 55%; a yearly increase of 1.1%.

Primary energy use

This study aimed at identifying the potential for energy efficiency improvement in industrial final energy demand. However, it is also important to see what the potential for energy efficiency improvement in primary energy use would be.

In 2009, the industrial sector consumed more than 80 EJ of fuels and more than 24 EJ of electricity. The current global average conversion efficiency for power generation is 38% (IEA, 2011c) while the transmission and distribution losses account for about 8.6% of the net electricity production (World Bank, 2013). Based on this, the 2009 primary industrial energy use, i.e. the final energy use plus the energy used for power generation, is estimated at 151 EJ.

Current global average conversion efficiencies are 33% for coal, oil and nuclear plants, and 37% for natural gas plants (IEA, 2011c). Based on the development of the conversion efficiencies in the period 2009-2035 in the World Energy Outlook, we estimate that in 2050, under the reference scenario, the global average conversion efficiencies will rise to 41% for coal, 34% for oil, 47% for natural gas, and to 33% for nuclear plants. The 2050 world average conversion efficiency is estimated at 45% based on the conversion efficiency per different power source and the 2050 fuel mix used for power generation reported in IEA (2012) under the 6DS. In 2050, industrial electricity consumption will overcome the 62 EJ while the industrial primary energy use is estimated to reach 273 EJ (see Figure 2-12).

Current BPT energy efficiencies are 47% for coal, 50% for oil, 60% for natural gas and 39% for nuclear plants (Graus et al., 2011; Graus and Worrell, 2011), while energy efficiency improvements in hydropower plants (100% energy efficiency in IEA[20]) can increase the throughput by 12% (Graus et al,. 2011). Based on the fuel mix breakdown for power generation in 2050 reported in IEA (2012) under the 6DS, it is estimated that the worldwide BPT adoption has the potential to increase the world average energy efficiency for power generation to 53%; an energy efficiency improvement of 16% compared to the 2050 reference case.

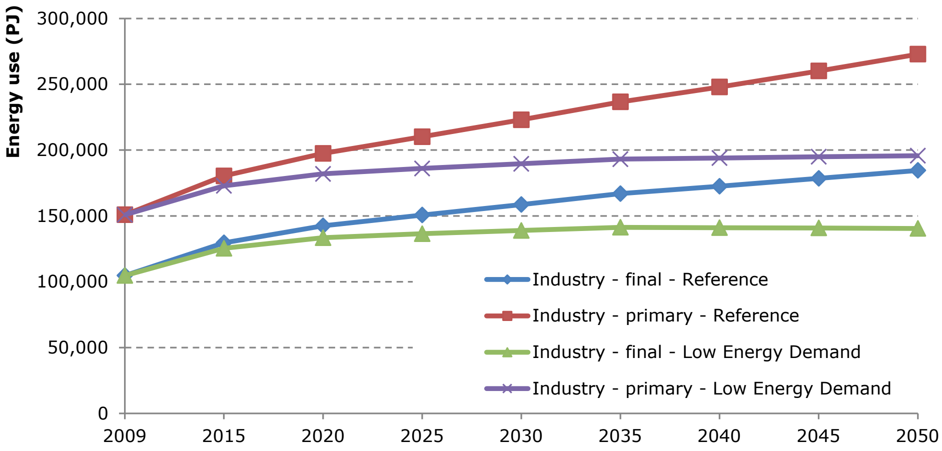

Figure 2-12 Final and primary energy use in the reference and the low energy demand scenarios

Energy efficiency improvements in the various industrial sub-sectors have the potential to decrease the final energy use from 185 EJ to 140 EJ (24% energy savings potential) and the primary energy use from 273 EJ to 213 EJ (22% energy savings potential). Improvements in power generation can further reduce the primary energy use by 8% to 196 EJ. In total, 77 EJ can be saved (28% energy savings potential); 60 EJ from lower industrial energy demand (44 EJ direct energy savings and 15 EJ indirect energy savings due to the reduced energy losses in power generation) and 18 EJ from energy efficiency improvements in power generation.

Measure inclusion

A number of important measures that have the potential to substantially contribute to a more energy efficient industrial sector were not included in this analysis. The combined production of heat and power (CHP) is such a measure. According to the IEA (2012), increasing the use of CHPs would decrease the current final energy use by more than 1.5 EJ in the chemical and petrochemical industry and by 0.2 EJ in the pulp and paper industry. Saygin et al. (2011b) estimates that the adoption of CHPs in the chemical and petrochemical sub-sector has the potential to decrease the final energy use (2006) by 1.3 ± 0.1 to 3.5 ± 0.2 EJ depending on the

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[20] In the IEA energy statistics, the default conversion factor used for converting electricity generation from hydropower to primary energy is 100%.

reference efficiency of the separate heat and power generation units replaced. CHPs can contribute to increased energy efficiency in the industrial sector, it would thus be of interest for future studies to further investigate the energy savings option.

In addition, improving product design will result in lower industrial energy use. According to Worrell et al. (1995) efficient product design can reduce energy use for plastics production by 14%. Hekkert et al. (1998) identified the potential for decreasing the European CO_2 emissions in the period 2000-2020 that are related to packaging, by 50% through reusable packaging, lighter packaging, material substitution and the use of recycled material. Material efficiency options in metal manufacturing such as yield improvement will result in lower amounts of liquid metal needed for the production of the final product decreasing therefore the energy needed for re-melting and processing. According to Milford et al. (2011) optimizing the yield through the elimination of scrap generation could decrease the 2007 energy use in steel manufacturing by 17% and in aluminium manufacturing by 6%.

The measures used in this report are limited to the ones commercially available today. The inclusion of technologies that are currently on a demonstration or pilot phase and will likely be commercially available in the near future were not taken into consideration. The inclusion of innovative technologies such as new separation membranes would result in a higher energy savings potential.

2.5 Conclusions

The industrial sector is a major energy consumer, responsible for 29% of the global final energy consumption (including coke ovens, blast furnaces and excl. feedstocks). Industrial energy use increased from 67 EJ in 1971 to 83 EJ in 1990 to reach its peak in 2008 at 108 EJ; a yearly increase of 1.2%. In 2009, industries consumed 105 EJ (3.0% lower from the 2008 level mainly due to the economic downturn). In 2050, under the reference scenario which represents a continuation of recent trends, industrial energy use is estimated to almost double to 185 EJ.

Industrial activities are responsible for a major part (around 40%) of global greenhouse gas emissions. The implementation of energy efficient technologies and practices can lead to reduced energy use and GHGs. According to this analysis, the implementation of energy efficiency improvement measures can reduce the industrial energy use from 185 EJ in 2050 in the reference scenario to 140 EJ in the low energy demand scenario; a decrease of 24%. Potential benefits, besides mitigating GHG, could include reduced energy costs, improved capacity utilization, enhanced productivity and increased competitiveness. Other potential benefits, albeit less quantifiable, could include limited resource exploitation, energy price reduction, improved energy security, job creation etc.

Energy efficiency can play an important role in mitigating climate change. However, to reduce the global greenhouse gas emissions by more than 50% in 2050, new technologies will need to be employed in the industrial sector while fossil fuel sources will need to be replaced by renewable sources. To achieve such drastic changes, effective policies will need to be designed and Research and Development (R&D) will need to be promoted.

Overall, 44 EJ can be saved with the implementation of energy saving measures. The most energy savings can be implemented in the Others industrial sub-sector and then follow the iron and steel and the chemical and petrochemical industrial sub-sectors.

Under the reference scenario, the industrial energy use for the period 2009-2050, will most drastically increase in India (224%), the Rest of developing Asia (158%), Africa (101%) and Middle East (103%). The lower increase will take place in OECD countries; OECD Europe (23%), OECD Americas (20%) and OECD Asia Oceania (19%), while China, Latin America and the Transition economies will experience an increase of 83%, 94% and 69% respectively.

Under the low energy demand scenario, in which there is a wide adoption of energy efficiency measures, industrial energy use will mostly increase in India (155%), the Rest of developing Asia (107%), Middle East (61%) and Africa (49%). For the remaining regions the increase in energy use increase will be limited to 36% for China, 41% for Latin America and 8% for OECD Europe. In OECD Americas and OECD Asia Oceania the energy use for the 2009-2050 period will not increase.

The largest share of the global estimated technical savings potentials, 36%, is identified in China. And then follow the Transition economies (15%) and India (9%). The regions with the lowest share in global energy savings are OECD Europe, OECD Asia Oceania, Africa and Middle East, with a share of about 4% each. This is mainly due to their low share in the global industrial energy use in the 2050 reference scenario that ranges between 4 and 8%.

The results of this study highlight the importance of industrial energy efficiency by synthesizing/integrating and providing deeper insights of the energy savings potentials in different regions of the world. To limit industrial energy use and GHG emissions strong policies will need to be implemented as actions are required to ensure that new plants built operate at state-of-the-art levels and older plants are retrofitted with more energy efficient measures. To determine the future potentials more accurately for energy efficiency improvements per industrial sub-sector and world region, further research is required using more bottom-up details able to capture the specificity of each industry, particularly in major industrial energy consuming regions.

Acknowledgements

This study is based on previous studies concerning energy demand scenarios prepared for Greenpeace/EREC and UBA in cooperation with DLR. The views and research in this study do not necessarily represent their views.

Appendix 2A Energy savings potentials – sensitivity analysis

Table 2-11 Energy savings potentials in 2050 (annual autonomous energy efficiency improvement = 0.25%)

	Iron and steel		Primary aluminium		Chemicals & petrochemicals		Non-metallic minerals		Pulp and Paper		Other industries	
World regions:	fuels	electricity	fuels	electricity	fuels	electricity	fuels	electricity	fuels	electricity	fuels	electricity
OECD Europe	9%	9%	17%	27%	30%	17%	34%	20%	22%	22%	17%	16%
OECD Americas	20%	20%	20%	27%	30%	17%	46%	35%	22%	22%	28%	21%
OECD Asia Oceania	26%	26%	17%	23%	30%	17%	33%	20%	22%	22%	27%	22%
China	43%	43%	51%	24%	30%	17%	22%	5%	22%	22%	36%	25%
Latin America	51%	51%	1%	26%	30%	17%	26%	15%	22%	22%	34%	30%
Africa	38%	38%	44%	25%	30%	17%	38%	6%	22%	22%	37%	22%
Middle East	-	-	-	26%	30%	17%	34%	14%	22%	22%	29%	19%
Transition Economies	59%	59%	58%	31%	30%	17%	63%	30%	22%	22%	52%	36%
India	32%	32%	34%	27%	30%	17%	17%	-	22%	22%	29%	26%
Rest of developing Asia	-	-	-	25%	30%	17%	33%	17%	22%	22%	26%	14%
World	39%	38%	36%	26%	30%	17%	29%	10%	22%	22%	30%	24%

Table 2-12 Energy savings potentials in 2050 (annual autonomous energy efficiency improvement = 0.75%)

	Iron and steel		Primary aluminium		Chemicals & petrochemicals		Non-metallic minerals		Pulp and Paper		Other industries	
World regions:	fuels	electricity	fuels	electricity	fuels	electricity	fuels	electricity	fuels	electricity	fuels	electricity
OECD Europe	-	-	-	10%	15%	0%	34%	20%	5%	5%	8%	5%
OECD Americas	2%	2%	2%	10%	15%	0%	46%	35%	5%	5%	14%	5%
OECD Asia Oceania	9%	9%	-	5%	15%	0%	33%	20%	5%	5%	12%	7%
China	31%	31%	40%	7%	15%	0%	22%	5%	5%	5%	26%	12%
Latin America	39%	39%	-	10%	15%	0%	26%	15%	5%	5%	23%	16%
Africa	24%	24%	32%	9%	15%	0%	38%	6%	5%	5%	25%	8%
Middle East	-	-	-	9%	15%	0%	34%	14%	5%	5%	14%	6%
Transition Economies	50%	50%	48%	15%	15%	0%	63%	30%	5%	5%	42%	24%
India	16%	16%	20%	10%	15%	0%	17%	-	5%	5%	16%	10%
Rest of developing Asia	-	-	-	9%	15%	0%	33%	17%	5%	5%	22%	3%
World	27%	26%	24%	9%	15%	0%	29%	10%	5%	5%	20%	10%

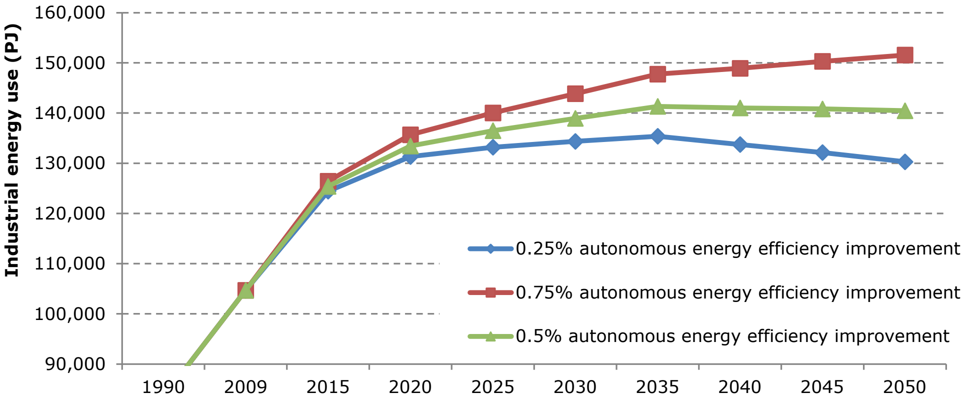

Figure 2-13 Industrial energy use in the low energy demand scenario under different autonomous energy efficiency improvements

3 Energy efficiency improvement and GHG abatement in the global production of primary aluminium [21]

Abstract

Primary aluminium production is a highly energy intensive and greenhouse gas (GHG) emitting process responsible for about 1% of global GHG emissions. In 2009, the two most energy intensive processes in primary aluminium production, alumina refining and aluminium smelting, consumed 3.1 EJ, of which 2 EJ was electricity for aluminium smelting; about 8% of the electricity use in the global industrial sector. The demand for aluminium is expected to increase significantly over the next decades, continuing the upwards trend in energy use and GHGs. The wide implementation of energy efficiency measures can cut down GHG emissions and assist in the transition towards a more sustainable primary aluminium industry.

In this study, 22 currently available energy efficiency measures are assessed, and cost-supply curves are constructed to determine the technical and the cost-effective energy and GHG savings potentials. The implementation of all measures was estimated to reduce the 2050 primary energy use by 31% in alumina refining and by 9% in primary aluminium production (excluding alumina refining) when compared to a "frozen efficiency" scenario. When compared to a "business-as-usual" (BAU) scenario, the identified energy savings potentials are lower; 12% and 0.9% for alumina refining and primary aluminium production (excluding alumina refining), respectively.

Currently available technologies have the potential to significantly reduce the energy use for alumina refining while in the case of aluminium smelting if no new technologies become available in the future, the energy and GHG savings potentials will be limited.

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[21] Based on Kermeli, K., P.H. ter Weer, W. Crijns-Graus, and E. Worrell. (2015). Energy efficiency improvement and GHG abatement in the global production of primary aluminium. *Energy Efficiency* 8, 629–666.

3.1 Introduction

The primary aluminium industry comprises one of the top five most energy intensive industries, following the chemicals and petrochemicals, iron and steel, cement, and pulp and paper industries (IEA, 2007). In 2009, the final energy consumption for primary aluminium production was about 3.1 EJ[22], equivalent to 3% of the total final industrial energy use (excluding industrial non-energy use) (IEA, 2011a). Aluminium smelting is a highly electricity intensive process consuming about 2 EJ of electricity, equivalent to 8% of the industrial sector's electricity use. The 2009 energy use for alumina refining, the second most energy intensive process step in the primary aluminium production route, is estimated at 1.1 EJ.

The production of primary aluminium is a multi-stage process. Initially, bauxite ore is resolved/digested and refined into alumina in the Bayer process. Alumina is then transformed into aluminium in an electrolytic cell with the Hall-Héroult process. Molten aluminium is cast into ingots which are transferred and further processed in aluminium foundries. Aluminium can also be produced from scrap, in the secondary production route. Only 5% of the energy needed to produce primary aluminium is required to produce aluminium from scrap (IEA-ETSAP, 2012).

The primary aluminium industry is a large energy consumer and a major greenhouse gas (GHG) emitter as next to the emitted greenhouse gas emissions during fuel combustion and electricity generation, perfluorocarbons (PFCs) are emitted. PFCs are gases with a high global warming potential (GWP), ranging from 6,500 times for tetrafluoromathenane (C_2F_4) and 9,200 times for hexafluoromethane (C_2F_6) the GWP[23] of carbon dioxide (CO_2) (IPCC, 2006b). In 2007, the primary aluminium industry emitted a total of about 400 Mt CO_2-equivalent of GHGs; equivalent to about 1% of global greenhouse gas emissions (IEA, 2009b). [24] For the same year, the International Aluminium Institute (IAI) estimates global PFC emissions from aluminium smelting at about 29 Mt CO_2-eq (IAI, 2013b).

Several studies have addressed the potential for energy efficiency improvements (Saygin et al., 2011) and greenhouse gas mitigation (Gale and Freund, 2001; Luo and Soria, 2007). However, there is currently no study that analyzes the energy and GHG savings potentials of the major energy saving technologies/measures on a country level. Main constraints for a more detailed analysis have been the level of data aggregation. The IAI provides energy use data for alumina and primary aluminium production on a regional level while the International Energy Agency

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[22] Estimate based on the 2009 average energy use for alumina refining and aluminium smelting and the 2009 global metallurgical grade alumina and primary aluminium production (IAI, 2013c).

[23] The GWPs used in this analysis are the 100 year values reported in the second IPCC Assessment Report (IPCC, 1995).

[24] It includes CO_2 emissions from fuel combustion, indirect CO_2 emissions from electricity consumption and process emissions from aluminium smelting. The most important process emissions in primary aluminium production are i) CO_2 emissions released during the consumption of carbon anodes, and ii) PFC emissions released when the alumina concentration in the electrolytic cell drops below a critical point.

(IEA) provides energy data on a country level but they concern the non-ferrous metals industry as a whole[25].

This study aims to provide a detailed analysis of the current and future energy savings and GHG abatement potentials in the global primary aluminum industry. To achieve this, a bottom-up, computational model of the primary aluminium industry is developed, to construct cost-supply curves depicting the energy and GHG savings potentials and the costs per country. Two scenarios are developed, the "frozen efficiency" and the "business-as-usual" scenarios. The "frozen efficiency" scenario estimates the energy and GHG development when energy intensity remains at current levels, and the "business-as-usual" when progress takes place based on historical rates.

In addition, this study attempts to investigate the potentials for energy savings in alumina refining. Main reason is that, and as already identified in several studies (Saygin et al., 2011; Green, 2007), although alumina refining is a less energy intensive process than aluminium smelting, it offers potentially large savings in the production chain of aluminium. According to Saygin et al. (2011) the worldwide adoption of Best Practice Technology (BPT) in the primary aluminium industry can decrease the energy use by 24%, with improvements in alumina refining being responsible for 80% of the total savings potential. The relatively low energy savings potential identified for aluminium smelting reflects the fact that the smelting of aluminium, following its identification as a major energy intensive process, has already been significantly optimized (Green, 2007). In addition, innovative technologies, able to further decrease energy use, are still in pilot phase.

In this paper, we give an overview of the primary aluminium industry, briefly describing the main processes, along with the energy intensities and the main sources of greenhouse gas emissions (Section 3.2). We then describe the methodology followed to construct the cost-supply curves in Section 3.3 and give an overview of the most important energy efficiency improvement technologies/measures in Section 3.4. In Section 3.5, we present the results and the discussion and in Section 3.6 the conclusion along with our recommendations.

3.2 Overview of the primary aluminium industry

Although aluminium is a relatively new material, produced for the first time in early 1800, its wide versatility has triggered demand and primary aluminium production surpassed the 49 Mtonnes in 2013. That is about two times the 2001 production and more than four times the 1973 production, or an average annual growth within the 1973-2013 period of 3.6 % but grew more rapidly in later years. The aluminium industry faces a growing demand with the main driver being China.

The structure of the primary aluminium industry is not the same as 40 years ago. Alumina production has shifted from industrialized or primary aluminium producing countries (i.e. United States, Japan, Canada, France and Germany), to countries rich in bauxite reserves (IAI,

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[25] In 2009 the non-ferrous metals industry consumed about 4.3 EJ (IEA, 2011a). It is estimated that the two most energy intensive steps in primary aluminium production (alumina refining and aluminium smelting) were responsible for about 72% of the energy consumed in the non-ferrous metals industry.

2013d). A similar shift has been observed in the aluminium smelting industry. Three countries, United States, Union of Soviet Socialist Republics (USSR) and Japan responsible for 60% of primary aluminium production in the early 1970s, currently supply only 10% of primary aluminium. In the past years, aluminium production has grown in Australia, Canada, Russia, China and Middle East with main reason for most countries being the low electricity costs (IAI, 2013d).

Electricity and alumina costs account for about 22 and 31% of production costs respectively (Bergsdal, 2004), therefore, access to abundant and low-cost electricity and alumina is of major importance. New aluminium smelting plants are usually built in areas where production costs are low. According to IAI (2013d), in 2009, 38% of electricity used in aluminium smelting came from hydropower. Countries with abundant hydropower are Brazil, Canada, Norway and Russia.

Energy efficiency in aluminium smelting has notably improved over the past decades. In the 1950s electricity use amounted to 21 MWh/tonne aluminium (Bergsdal et al., 2004) and decreased to 17 MWh/tonne in the 1980s. Current world average energy use has reached 14.8 MWh/tonne aluminium (IAI, 2013c). Some developing countries currently have some of the lowest energy intensities, since new plant capacities installed were based on more recent and efficient technologies.

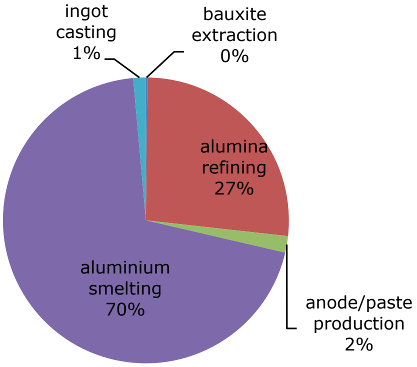

Figure 3-1 Energy use breakdown in primary aluminium production (based on data reported in IAI, 2013a)

3.2.1 Production processes and energy use

As shown in Figure 3-1, the most energy intensive processes in primary aluminium production are alumina refining and aluminium smelting, responsible for 27% and 70% of energy use, respectively. Anode production is responsible for about 2%, while aluminium casting for about 1.4% of the energy use (IAI, 2013a).

Bauxite extraction

Bauxite ore is usually mined in open pit mines, in certain cases washed and dried, and when originating from forested areas also beneficiated. Energy use is mainly fuel used by excavating equipment and varies based on the depth of bauxite sources. The 2010 IAI Life Cycle Inventory (LCI), reports an energy use of 23 MJ/tonne bauxite (IAI, 2013a), while the 2005 data on the North American aluminium industry give an energy use of 216 MJ/tonne bauxite (Green, 2007). Approximately 2.9 tonnes of bauxite are required to produce 1 tonne of alumina (IAI, 2013a).

Alumina refining

Bauxite is transferred to alumina refineries for the production of alumina. The process most widely used is the Bayer process in which bauxite is forwarded to a series of digesters where it is dissolved in most cases in a mix of sodium hydroxide and sodium carbonate under pressure and temperature (BCS, 2007). The product of digestion, “green liquor” is then clarified to remove the undesirable bauxite residue, commonly known as “red mud”, and the alumina hydrate dissolved in the liquor is subsequently precipitated (“crystallized”) and calcined (removal of crystal water) in rotary or stationary calciners. Typical energy use is 4-10 GJ/tonne for digestion and evaporation and 3-4.5 GJ/tonne for calcination. In addition, electricity needs raise the overall energy use by another 1.0 GJ/tonne (Henrickson, 2010). The total energy consumption in alumina refining is mainly influenced by the quality of bauxite ore, the selected digestion technology, the type of calciner (IPTS/EC 2013), and the plant liquor productivity (“yield”) (Donaldson, 2011).

Bauxite quality plays an important role in energy use. The use of bauxite with high water content will increase the energy use due to higher evaporation needs (IPTS/EC, 2013). In addition, mono-hydrate bauxite ores (boehmite and diaspore) require higher pressure and temperature in digestion than tri-hydrates (gibbsite) (IPTS/EC, 2013; BCS, 2007). Also, a high reactive silica content results in increased operating costs as it reacts to form sodium aluminium silicates which precipitate, binding aluminium and sodium values. Bauxites with high silica content (8-15%) are processed in alternative and more energy intensive processes than the Bayer to improve alumina and sometimes sodium recovery. Such processes are the Combined Bayer-Sinter, the Sinter, the Flotation-Bayer and the Lime-Bayer processes. Table 3-1 presents typical energy intensities.

Table 3-1 Energy intensities for different alumina refining processes

	Bayer	Sinter	Combined Bayer-Sinter	Flotation-Bayer	Lime-Bayer	Nepheline
GJ/tonne alumina	8-13.6[1]	36-40.5[2]	21-52[3]	16.0-16.1[4]	16.3[5]	50[6]

[1]IPTS/EC, 2013; Smith, 2009, Liu et al., 2010, [2]Smith, 2009; Liu et al., 2006, Liu et al., 2010 [3] Liao and Li, 2010; Li et al., 2008; Liu et al., 2006, [4]Li and Yang, 2010; Liu et al., 2010, [5]Liu et al., 2010, [6]Smirnov, 1996

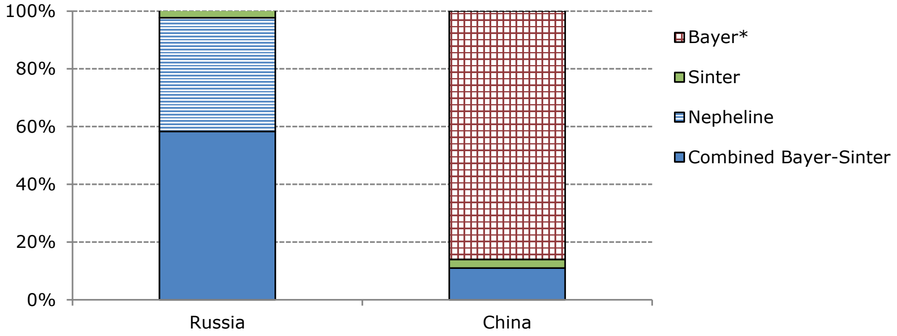

Figure 3-2 Production shares of the various alumina refining processes in 2009, in China and Russia [based on UC Rusal (2010) for Russia and Gu and Wu (2012) for China]
*includes alumina produced with the Bayer, Flotation-Bayer and the Lime-Bayer processes. In 2005, about 13% of Chinese alumina production derived from the Bayer process (Yanjia and Chandler, 2009).

The Combined Bayer-Sinter and the Sinter processes have been widely used in China and Russia due to the low quality bauxite reserves available in these regions. It is reported that China decreased the Combined Bayer-Sinter share from 88% in 2005 (Yanjia and Chandler, 2009) to 15% in 2009 (Gu and Wu, 2012) significantly decreasing its energy use. In a few areas in Russia and Iran, alumina is produced from nepheline concentrate[26]. The Nepheline process produces a variety of materials (i.e. cement, soda, potash and alumina). Figure 3-2 shows the share of the different processes in alumina production in China and Russia in 2009.

In the digestion area, tube digestion in which the bauxite slurry is heated without being diluted with live steam, is considered an energy efficient technology for bauxites requiring high temperature digestion (temperature >240°C). In the calcination area, stationary kilns, due to improved waste heat recovery, consume 30% less energy than rotary calciners (Missalla et al., 2011; Klett et al., 2011).

A key factor affecting energy consumption in alumina refineries is the plant liquor yield – the alumina produced per cubic meter of liquor pumped around the Bayer plant (Henrickson, 2010; Hudson et al. 2005; Donaldson, 2011). The alumina throughput is equal to the flow times the yield. Hence, increasing the refinery's yield will translate into a lower flow needed to satisfy production, and therefore decreasing the energy requirements (Henrickson, 2010).

Optimizing the alumina refining process can reduce the energy use to below 7 GJ/tonne alumina in alumina refineries using tube digestion and below 10 GJ/tonne alumina for a conventional digestion system (IPTS/EC, 2013).

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[26] Nepheline concentrate is a by-product deriving from beneficiation factories, which contains about 25-30% alumina and 44% silica (Smirnov, 1996).

In 2009, the worldwide average energy use in alumina refining was 14.6 GJ per tonne of alumina (IAI, 2013c). More than 90% of the energy used is fuel with the remainder being electricity (IAI, 2013a). The energy use in alumina refining has experienced an annual decrease of 0.4% during the 1998 to 2012 period.[27] Table 3-2 shows the energy use in the six top alumina producing countries in 2009.

Table 3-2 Alumina production and energy intensity in the main alumina producing countries in 2009

Countries	Alumina production (10^3 tonnes)[1]	Estimated alumina production-metallurgical grade (10^3 tonnes)[2]	Share on global production (%)	Energy intensity[3] (GJ/tonne alumina)	Sources for energy use
China	23,800	22,938	31%	19.4	IAI, 2013c
Australia	19,948	19,649	26%	10.5	AAC, 2012
Brazil	8,618	8,544	11%	9.6[4]	IAI, 2013c
India	3,900	3,347	5%	14.4	Trudeau et al., 2011
Russia	2,794	2,568	4%	27.9[5]	own calculations based on UC Rusal, 2010; Liu et al., 2010
United States	2,370	1,961	3%	14.4	Green, 2007
Rest	15,270	13,268	20%	N/A	-
Total	76,700	72,723	100%	14.6	IAI, 2013c

[1] Alumina production data are taken from USGS (2012b).

[2] Reported alumina production on a country level, includes alumina produced for metallurgical and chemical purposes. Most of alumina produced (about 94% in 2009) (IAI, 2013c) is of metallurgical grade. To exclude the chemical grade alumina production we use the regional shares of metallurgical alumina to the overall alumina production reported by IAI (2013c) (see Table 3-14 in Appendix3A).

[3] Energy intensity in alumina refineries in 2009. When no data are available for 2009 the most recent available data found in literature are used.

[4] Due to the lack of data, the energy use of the Brazilian alumina industry is assumed to be equal to the 2009 energy use in Latin America as reported by the IAI (2013c). The fuel oil consumption for alumina refining reported in Brazilian statistics (Ministerio de Minas E Energia, 2012), translates into a very low energy intensity of about 5 GJ/tonne alumina, which most probably only accounts for the calcination process.

[5] Estimated based on the 2009 share of the different alumina refining production processes in Russia (see Figure 3-2) and an energy intensity of 26 GJ/tonne for the Combined Bayer-Sinter process (Liu et al., 2010) and 38 GJ/tonne alumina for the Sinter process (Smith, 2009). This value does not take into account alumina production with the Nepheline process.

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[27] This was estimated based on the reported energy use for alumina refining (IAI, 2013c) for the 1998-2012 period. Although energy use data are also available for earlier years, China started reporting energy use data in 1998.

Carbon anode production

Carbon anodes are consumed during electrolysis. There are two types of carbon anodes used in electrolytic cells; i.e. Söderberg (in-situ baked) and prebaked anodes. Prebaked anodes are more energy efficient and are characterized by lower perfluorocarbon and process CO_2 emissions (see Table 3-4). There are two types of Söderberg anodes; Vertical Stud Söderberg (VSS), and Horizontally Stud Söderberg (HSS), and three types of prebaked anodes, varying in the way the busbars transfer electric current to the electrolytic cell; Side-Worked prebake cells (SWPB), Center-Worked prebake cells (CWPB), and the most energy efficient, prebake cells with Pointfeeding system (PFPB). All new primary aluminium producing facilities install PFPB cells (BCS, 2007). Currently, about 90% of aluminium is produced in prebaked cells (IAI, 2013a).

Anode production facilities can be situated at the smelting site or in specialized anode baking facilities. Prebaked anodes are made from calcined petroleum coke, coal tar or petroleum pitch and cleaned recycled anodes (butts) (BCS, 2007; IPTS/EC, 2013) which are baked in open or closed ring furnaces at 1100ºC (IPTS/EC, 2013). According to the 2010 LCI the energy requirements are 526 MJ/tonne and 3,750 MJ/tonne for Söderberg and prebake anodes respectively. Electrolysis in prebake cells requires 0.43 tonnes of anode while Söderberg electrolysis 0.53 tonnes of anode per tonne aluminium produced (IAI, 2013a). Best practice technology energy use for prebake anode baking is 2.8 GJ/tonne anode (Worrell et al., 2008).

Aluminium smelting

Primary aluminium is produced with the electrochemical reduction of alumina by the Hall-Héroult process. The Hall-Héroult process takes place in an electrolytic cell consisting of two electrodes, an anode and a cathode, separated by an electrolytic bath (usually cryolite). A direct current (DC) enters through the anode into the electrolytic bath where alumina is dissolved and exits through the cathode. The DC current reduces alumina into aluminium and oxygen. Aluminium is extracted through siphons at the upper part of the cathode, and oxygen reacts with the carbon anode to form carbon dioxide (BCS, 2007).

The Hall-Héroult process is the most energy intensive step in the primary aluminium production chain, responsible for nearly 70% of the overall final energy consumed and 98% of the electricity consumed (IAI, 2013a). Electricity use differs per type of electric cell with the typical values shown in Table 3-4. According to the 2010 LCI, Söderberg cells consume 17.2 MWh/tonne aluminium and prebake cells 15 MWh/tonne aluminium (IAI, 2013a). Electricity use in state-of-art smelters is about 13.5 MWh per tonne (IEA, 2009b).

In 2009, the world average electricity use[28] was 14.8 MWh/tonne of primary aluminium (IAI, 2013c). During the past two decades, the energy use in aluminium smelting has experienced an annual decrease of 0.4% (IAI, 2013c). Electricity use differs between the different countries

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[28] In this study, and unless otherwise mentioned, electricity use refers to alternating current (AC) electricity. AC electricity is the DC electricity plus the electricity use in auxiliary components. Electricity use in alumina refining, anode manufacture and ingot casting is not included.

due to the different cell technologies employed and the level of energy efficiency. Table 3-3 shows the primary aluminium production in the top primary aluminium producing countries.

Table 3-3 Primary aluminium production and energy intensity in the main primary aluminium producing countries in 2009

Countries	Primary aluminium production (10^3 tonnes)[1]	Share in global production (%)	Electricity intensity (MWh/tonne aluminium)	Sources for energy use
China	12,900	35%	14.2	IAI, 2013c; IEA, 2012; Li and Yang, 2010
Russia	3,815	10%	14.9	IEA, 2012
Canada	3,030	8%	14.7[2]	own calculations based on CIEEDAC, 2012
Australia	1,943	5%	15.0	AAC, 2012
United States	1,727	5%	15.4	IEA, 2012
India	1,598	4%	14.9	IEA, 2012
Brazil	1,536	4%	15.6	IEA, 2012
Norway	1,130	3%	13.5[3]	Grimsrud and Kvinge, 2006
United Arab Emirates	1,010	3%	14.8[4]	IAI, 2013c
Bahrain	848	2%	14.8[4]	IAI, 2013c
South Africa	809	2%	14.9	IEA, 2012
Rest	6,754	18%		
Total	37,100	100%	14.8	IAI, 2013c

[1] Primary aluminium production data were taken from USGS (2012a).

[2] The electricity use reported in CIEEDAC (2012), 14.8 MWh/tonne aluminium, also includes the electricity use in alumina refining, anode production and ingot casting. To estimate the electricity use only for aluminium smelting, we initially estimate the electricity use in the remaining processes based on the alumina and primary aluminium 2009 production levels, the share of the prebake and Söderberg anodes in Canada (see Table 3-24 in Appendix 3A), and the average material and electricity requirements for each process step (based on IAI, 2013a) and subtract it from the reported value.

[3] 2005 electricity use.

[4] Due to the lack of data, the energy use for aluminium smelting in Bahrain and the United Arab Emirates is assumed to be equal to the energy use reported by the IAI for the Gulf Cooperation Council (GCC) region (Bahrain, Oman, Qatar and United Arab Emirates). Bahrain and the United Arab Emirates are responsible for 84% of primary aluminium production in the GCC region.

Ingot casting

After electrolysis, the liquid metal is kept in holding induction or reverberatory furnaces for alloying (IPTS/EC, 2013). Molten aluminium is then turned into solid shapes, through ingot casting, which will be further processed in extrusion, casting, and rolling facilities. Remelt ingot and recycled aluminium scrap are also used. In general, ingot casting is not very energy intensive. Based on the 2010 LCI about 1,120 MJ/tonne aluminium is used in ingot casting, of which 88% is fuel and 22% electricity (IAI, 2013a), while 2005 data on the North American aluminium industry give an energy use of 3,600 MJ/tonne aluminium (Green, 2007).

3.2.2 Greenhouse gas emissions

Primary aluminium production is a significant source of carbon dioxide (CO_2) and perfluorinated hydrocarbon (PFC) emissions. CO_2 emissions are generated during i) anode consumption (process CO_2 emissions)[29] and ii) fuel combustion and electricity generation (when based on fossil fuel use). In addition PFCs, CF_4 and C_2F_6, gases with 6,500 and 9,200 times the global warming potential of CO_2 respectively (IPCC, 2006b), are emitted when the alumina content in the electrolytic cell drops below a critical level, a critical condition known as the "anode effect". Based on the IAI (2013c), in 2009 about 22.1 $MtCO_2$-eq were emitted. According to the same source, the global mean PFC emission intensity decreased from about 4.5 in 1990 to 0.59 tCO_2-eq/tonne aluminium by 2009.

Table 3-4 shows the typical process CO_2 and mean PFC emission intensities per different type of cell technology in 2009. PFC emissions depend on the duration and frequency of anode effects and the overvoltage during the effect. Improved process control and alumina point-feeding systems can limit the occurrence and duration of anode effects (IPTS/EC, 2013).

Table 3-4 Energy intensity and PFC and process CO_2 emission intensity per cell technology type (Schwarz et al., 2001; IAI, 2013c and IAI, 2013a)

Cell technology	Energy intensity (MWh/tonne aluminium)[1]	2009 mean PFC emission intensity (tCO_2-eq/t aluminium)	Process CO_2 emissions (tCO_2/t aluminium)	Technology distribution
CWPB	14.6	0.7	1.5	3%
PFPB (non-China)	14.4	0.3		43%
PFPB (China)		0.7		44%
SWPB	15.5	4.3		1%
VSS	16.1	1.0	1.6	8%
HSS	16.6	1.3		1%
Overall	14.8	0.6	N/A	100%

[1] The energy intensities per different cell type are based on 1995 data (Schwarz et al., 2001).

The indirect CO_2 emissions from electricity consumption in smelting, depend on the fuel mix used for electricity generation in each country.

3.3 Methodology

A bottom-up model has been constructed to generate energy and greenhouse gas cost-supply curves for the major alumina and primary aluminium producing countries. The model uses disaggregated data on the specific energy use[30] of the different processes in the various countries.

Cost-supply curves are a useful tool, used to present the cost-effective as well as the technical energy and GHG savings potentials. To construct the curves, the most important energy and

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[29] The majority of process related CO_2 emissions derive from the reaction of alumina with the anode ($2Al_2O_3+3C \rightarrow 4Al+3CO_2$). The CO_2 emissions associated with the baking of prebake anodes account for less than 10% of the overall process related CO_2 emissions. (IPCC, 2006b)

[30] Specific energy use is the sum of the energy-related fuels and electricity used in the manufacture of the various products in primary aluminium production. Energy use for transportation and life cycle energy use is not taken into account.

GHG emission mitigating measures/technologies, commercially available today, are identified and ranked from low to high based on their Cost of Conserved Energy (CCE), or Cost of Mitigated Greenhouse Gases ($C_{CO2\text{-}eq}$). The cost-supply curves show in the y-axis the CCE or the $C_{CO2\text{-}eq}$ and in the x-axis the cumulative energy savings and the cumulative GHG emission savings. The width of each segment in the graph shows the energy or GHG savings potential of each energy efficiency improvement measure.

The CCE and the CMGE can be determined with the use of Eq. 3-1 and Eq. 3-2 respectively.

$$CCE = \frac{Annualized\ investment\ cost + Annual\ O\&M\ costs - Annual\ Financial\ benefits\ from\ energy\ savings}{Annual\ energy\ savings}$$

$$C_{CO2} = \frac{Annualized\ investment\ cost + Annual\ O\&M\ costs - Annual\ Financial\ benefits\ from\ energy\ savings}{Annual\ GHG\ emission\ savings}$$

The annualized investment cost is a function of the discount rate and the technical lifetime of the technology and can be calculated from Eq. 3-3.

$$Annualized\ investment\ cost = Investment\ cost \times \frac{d}{(1-(1+d)^{-n})}$$

Where d is the discount rate (%) and n the technical lifetime in years of the measure.

The cost-effective energy savings potential is defined as the sum of the energy savings potentials of all measures with a CCE less than zero. Technical energy savings potential is defined as the sum of all energy savings potentials of all the measures identified in this study. For the estimation of the technical potentials, no financial constraints are taken into consideration.

To determine the annualized investment costs, the discount rate needs to be defined. Social discount rates typically range between 6 and 8%, while private discount rates are relatively higher, and often range between 30 and 50% (Laitner et al., 2003). The use of higher discount rates aims at reflecting the hurdle rates of private investors to adopt energy efficiency measures (Worrell et al., 2004). The discount rates used in different studies vary considerably, with high discount rates being considered more representative of the industrial sector (Martin et al., 2000, Fleiter et al., 2009). In this study, to show the stakeholders' difficulty to invest in projects with high initial investment costs and long payback periods, a discount rate of 30% is used. To assess the cost-effectiveness of the different measures under different discount rates, a sensitivity analysis is performed in Section 3.5.

Energy consumption and GHG emissions in the primary aluminum industry can be reduced through the replacement or retrofitting of existing processes with technologies/measures with increased energy efficiency. The measures identified in this study are obtained from technical information found in literature and information offered from industry experts (see Section 3.4).

The methodology followed for the construction of the bottom-up model that generates cost-supply curves able to determine the cost- and non-cost-effective energy and GHG savings potentials for the primary aluminium is the following:

1.1 *Establish the base year.* For this study, 2009 was chosen as the base year, as it was the most recent year for which information on energy use for alumina refining and aluminium smelting was available on a country level.

1.2 *Determine the geographical boundaries.* It is very data intensive to include all the primary aluminium and alumina producing countries in the bottom-up model. For this reason, the top 11 primary aluminium (China, Russia, Canada, Australia, United States, Brazil, Norway, United Arab Emirates, Bahrain and South Africa) and top 6 alumina (China, Australia, Brazil, India, Russia and the United States) producing countries are taken into account responsible for the 82% and 80% of overall production, respectively (for more details on country production levels see Table 3-2 and Table 3-3).

1.3 *Determine the project boundaries.* The processes considered in this study are i) alumina refining, ii) anode production, iii) aluminium smelting, and iv) ingot casting. The energy use and GHG emissions of input material (i.e. caustic soda, limestone calcination and cathode carbon production) needed in the production of primary aluminum are excluded from this analysis.

1.4 *Determine the base year energy use and GHG emissions.* The 2009 energy consumption for alumina refining and aluminium smelting per country is estimated by multiplying the specific energy use and production in Table 3-2 and Table 3-3. Information regarding the energy use for anode production and ingot casting is not available on a country level. Therefore, in the case of anode manufacturing, we multiply the average energy use of Söderberg and prebake anode making with the primary aluminium production per different cell technology in each country. The estimated share of Söderberg and prebake technology per country is shown in Table 3-24 in Appendix 3A. In the case of ingot casting, we multiply the average energy use for ingot casting with the primary aluminium production.

To estimate the GHG emissions from fuel consumption, the overall fuel use is broken down per fuel type and then multiplied by the typical emission factor of the specific fuel (see Table 3-15 in Appendix 3A). The fuel mix used for each country is based on the reported fuel mix for the non-ferrous metals industry in IEA statistics (2011a) (see Table 3-16 in Appendix 3A).

GHG emissions from electricity use will depend on the fuel mix used for electricity generation and the associated conversion efficiency. Aluminium smelting relies heavily on hydropower with 38% of electricity in 2009 deriving from hydro sources (IAI, 2013d). As alumina refineries are primarily situated close to bauxite reserves[31] and not close to aluminium smelters, the electricity consumed is generated from a different fuel mix than in smelters. In this study, the fuel mix used for generating electricity consumed in alumina refineries is similar to the electricity coming from the grid in each country based on IEA statistics (2011a). For aluminium

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[31] It should be noted that this does not apply to U.S. and European alumina refineries, some of the Australian refineries, and two large Brazilian refineries.

smelters, we first define the share of hydropower on a country basis based on information available in literature, and then we break down the remaining share of electricity based on the fuel mix used in the grid. The fuel mix for electricity generation for alumina refining and aluminium smelting and the conversion efficiencies are given in Table 3-17, Table 3-18, and Table 3-19 in Appendix 3A.

3.5 Determine the baseline scenarios. To estimate the future cost- and non-cost-effective potentials, a baseline scenario that shows the future development of the energy demand in primary aluminium production needs to be determined. Future energy demand will be a function of primary aluminium demand.

3.5a. Future material demand

To estimate the future primary aluminium production, we assume that in the 2009-2050 period, primary aluminium production will increase with gross domestic product (GDP). According to CRU (2006), world average primary aluminium production is expected to reach 65 Mtonnes in 2025; an annual growth of 2.7% in the 2010-2025 period, analogous to about three quarters of global GDP growth.

Not all countries are expected to experience the same growth. In the case of China, primary aluminium production experienced a fivefold increase in the 1999-2009 period, while more recently, production increased by 40% from about 9 Mtonnes in 2006 to 13 Mtonnes in 2009 (IAI, 2013a). As in other countries, this growth is expected to decrease as the economy will start shifting from infrastructure to services. The reduction in China, however, is expected to be more significant than in other countries. The main reason is that the strong increase in the early 2000s, was due to favorable governmental conditions – around 80% of the outdated and energy intensive Söderberg aluminium smelters instead of shutting down, were renovated and increased their capacity – and not due to low production costs (CRU, 2006). Another reason Chinese smelting capacity increased, was due to the exploitation of electricity from isolated coal power plants that were difficult to connect to the grid (CRU, 2006). This cannot be sustainable in a country such as China, characterized by high electricity prices (see Table 3-5). Thus, primary aluminium production growth in China, after 2010, is expected to deteriorate drastically (CRU, 2006).

On the other hand, India's aluminium demand is expected to increase more in the future, since aluminium will be needed in the infrastructure, residential, automotive sectors and a growing aerospace industry.

In this study, we assume that the primary aluminium production growth rate in the top 11 primary aluminium producing countries will equal ¾ of GDP growth (based on CRU, 2006). Exceptions are China for which production growth will equal half of the increase in GDP growth and India for which production growth will equal the GDP growth. Secondary aluminium production is outside the project boundaries thus, the 2050's secondary aluminium production is not estimated. The GDP growth rates used are based on IEA (2011c) (see Table 3-20 in Appendix 3A).

As about 1.93 tonnes of alumina are required to produce 1 tonne of aluminium, the global alumina production in 2050 will equal 1.93 times the 2050 estimated global primary aluminium production. Important though for this study, is to estimate the alumina production in the top six alumina producing countries. Future alumina production in the different countries will primarily depend on production costs and the access to good quality and low-cost bauxite. In this study, an oversimplified method is used to determine future alumina production on a country basis. It is assumed that for the alumina exporting countries (Australia and Brazil) but also for India, the alumina production share on global production remains the same as in 2009. For China we assume that 14% of the alumina required in Chinese primary aluminium production is imported (same as in 2009) (based on Storesund, 2012). Similarly, we assume that 44% and 60% of alumina demand of U.S. (based on USGS, 2011) and Russian smelters (author own estimation[32]) respectively, is imported (same as in 2009).

Figure 3-3 shows the breakdown of alumina and primary aluminium production per different country in 2009, 2035 and 2050. We estimate that in 2050, global primary aluminium production will increase to 95 Mt while global alumina production will increase to 183 Mt; an annual increase of about 2.3%.

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[32] In 2009, Russian smelters produced 3.8 Mtonnes of aluminium. For an alumina requirement of 1.93 tonnes per tonne of aluminium, the alumina demand in Russian smelters was 7.4 Mtonnes. In 2009, Russian alumina refineries produced 2.8 Mtonnes of alumina. Assuming that all alumina produced was metallurgical, to satisfy the 2009 alumina demand in Russian smelters about 4.5 Mtonnes alumina had to be imported.

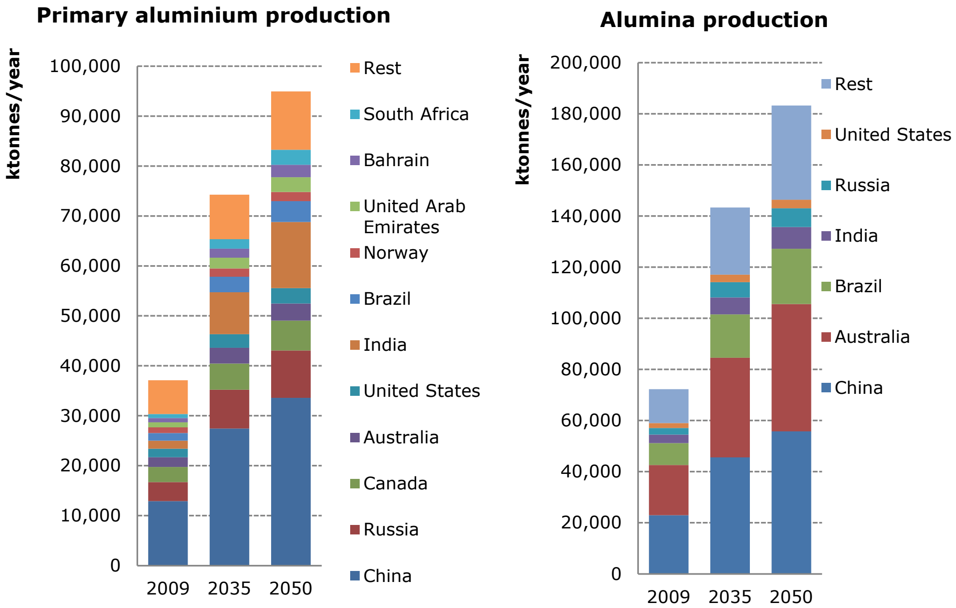

Figure 3-3 Estimated future primary aluminium and alumina production in the major producing countries

The future primary aluminium production estimated in this study, matches well with the production estimated by IEA (2012) under the low-demand scenario according to which, primary aluminium production will rise to 90-100 Mtonnes by 2050. In the same study and under the high-demand scenario, primary aluminium production is forecasted to increase to 120-135 Mtonnes.

Future primary aluminium and alumina projections have a great impact on the estimated future energy use and GHG emissions and the estimated energy and GHG savings potentials. The primary aluminium production in this analysis was based on future GDP trends. We used this approach to estimate the future primary aluminium production as many studies (Cleveland and Ruth, 1998; de Bruyn and Opschoor, 1997) have shown that an economy's material intensity increases with GDP and starts a decreasing trend as a certain income level is reached. As development takes place, economies industrialize and build up infrastructure, increasing the intensity of material use which starts decreasing when societies become more affluent, with their economies relying mostly on services. In this stage, when structural change occurs, de-materialization starts (Neelis and Patel, 2006). The degree of dematerialization can be debated though, as according to a recent study (Wiedmann et al., 2013) it can be lower than it was initially expected.

In reality, which countries will increase their share on world primary aluminium and alumina production will depend on their comparative advantage. Thus, this analysis could benefit from a more detailed way of projecting future production that takes into account parameters such as energy and raw material prices and trade.

3.5b. Baseline scenarios

The construction of different scenarios will assist to identify the energy efficiency improvement and GHG reduction potentials under alternative energy development situations. For the scenario analysis in this study two scenarios are constructed:

"frozen efficiency" scenario. According to the "frozen efficiency" scenario, the energy and GHG emissions intensity for all processes will remain stable at the 2009 level. Any change in energy consumption and GHG emissions will be the result of changes in production.

"business-as-usual" (BAU) scenario. In the BAU scenario, energy efficiency improvements take place in all processes over the years, representing a continuation of past trends. The energy intensity decreases at the historical rate of 0.4% per year (based on IAI, 2013c) in all processes except for aluminium smelting where a lower annual rate of energy efficiency improvement of 0.2% is used. We use a lower energy efficiency improvement as a significant part of the past energy efficiency improvements was due to the shutting down of Söderberg cells. It is considered that all new capacity installed will have all energy efficiency measures implemented and will operate close to BPT levels. In this scenario, it is assumed that all new smelter capacity will use PFPB technology and all old Söderberg cells will be phased out by 2050. In addition, all new alumina refineries built in China and Russia will use the Bayer process. We assume that reductions in energy use due to stock retirement are included in the annual energy efficiency improvement.

3.6 Identification of energy efficient technologies/measures. The measures that can significantly contribute to a less energy and GHG emission intensive primary aluminium industry are identified and described in Section 3.4. The energy savings potentials and the associated investment costs are determined based on available information in literature.

3.7 Implementation rates. Where possible, the implementation rates of energy efficiency technology/measures concerning alumina refining and aluminium smelting, are based on information found in literature, industry reports and company websites. For example, for one of the energy efficiency measures, tube digestion in alumina refining, the implementation rate was estimated based on the alumina plant capacity currently using tube digestion and on the alumina plant capacity that could adopt tube digestion (tube digestion can only be adopted by plants that use high-temperature digestion). For more details on how the implementation rates were estimated please see Table 3-23 and Table 3-24 in Appendix 3A.

Where no information of the current level of implementation could be retrieved, the implementation rates were estimated based on the gap between the current energy use and the BPT energy use (see Table 3-21 in Appendix 3A) and expert knowledge from industry specialists. BPT refers to the most advanced technology that is in use at an industrial scale (IEA 2012). Table 3-23 and Table 3-24 in Appendix 3A show the estimated implementation rates.

In the case of anode manufacture we use an implementation rate of 40% for each measure, estimated based on the current average energy use for anode baking and the BPT energy use and we apply it only to the share of prebaked technology. Also, for ingot casting we use the same implementation rate of 30% for each measure, estimated again based on the current average energy use for ingot casting and the BPT energy use.

3.8 Construction of cost-supply curves. The final step is the construction of the cost-supply curves based on Equations 3-1, 3-2 and 3-3. Important variables that affect the profitability of each energy efficient technology/measure in every country are the fuel and electricity costs. The bulk of fuel and electricity prices for industrial purposes were retrieved from the U.S. Energy Information Administration (EIA) International Energy Statistics (2013b) and the IEA Key World Energy Statistics (IEA, 2008) (see Table 3-5). As aluminium smelters are most usually situated close to low-cost electricity sources and alumina refineries close to bauxite sources, the price of electricity in alumina refineries and aluminium smelters differs. In this study it is assumed that anode production and ingot casting plants are situated close to the smelter and have access to the same low-cost electricity. We assume that all prices remain stable throughout the 2009-2050 period. To assess the impact energy prices have on the results we conduct a sensitivity analysis (see Section 3.5).

Table 3-5 Fuel and electricity prices in 2008, 2009 (EIA, 2013b; IEA, 2008)

	China	Russia	Canada	United States	Australia	Brazil	Norway	India	United Arab Emirates	Bahrain	South Africa
Natural gas ($/GJ)	10.5[1]	2.0	4.1	4.8	5.4[2]	11.8[3]	6.2[4]	4.0[5]	1.0[7]	1.0[6]	7.7[8]
Steam coal ($/GJ)	2.0[9]	1.7	2.4	3.1	3.0[10]	1.8[3]	4.5[4]	1.8	--	--	0.9[8]
Heavy fuel oil ($/GJ)	12.1[11]	8.5[12]	13.0	12.9	16.9[2,13]	6.8[3]	13.1[4]	12.7[14]	-[15]	--	10.7[14]
Electricity (alumina refining) ($/MWh)	105[16]	50	59[17]	68	51[2]	120	64	69[18]	--	--	22[9]
Electricity (aluminium smelting, anode production and ingot casting) ($/MWh)[19]	56	25	17	34	21	28	25	31	24	24	17

-- Not applicable; [1] Natural gas prices for the industrial sector vary considerably between the different Chinese provinces. In 2008, natural gas prices ranged between $5 and $15/GJ (IEA, 2009c). In this study we use an average price of $10.5/GJ; [2] These are the energy prices in the Australian primary metal and metal product manufacturing industry (ABS, 2010); [3] 2006 data (IEA, 2009a); [4] Energy costs in manufacturing mining and quarrying (Statistics Norway, 2010); [5] IEA, 2010; [6] 2006 data (ALBA, 2010); [7] Due to the lack of data it is assumed equal to the natural gas price in Bahrain; [8] 2005 data; [9] 2004 data; [10] (BREE, 2013); [11] Due to lack of data we use the 2008 heavy fuel oil price reported for Chinese Taipei; [12] (IEA, 2009a); [13] As oil consumption in the Australian industry is mainly diesel oil (EIA, 2013a), this energy price is for diesel oil; [14] 2007 data (IEA, 2009a); [15] No data are available, however the share of oil use in the fuel mix is low (see Table 3-16 in Appendix 3A); [16] IEA (2011b); [17] 2006 data; [18] Abeberese (2013); [19] 2009 electricity prices for smelters. Based on country and regional prices (CRU, 2010).

3.4 Review of energy efficiency improvements

In this section all identified measures are briefly described. A summary can be seen in Table 3-6 and Table 3-7.

Alumina Refining

Sweetening (1). Gibbsitic bauxite is characterized by higher solubility than boehmitic bauxite at the same temperature. The addition of gibbsite at the downstream of the high temperature digester, can significantly improve the alumina yield of processing boehmite (den Hond et al., 2007; Shah et al., 2004). Alumina yield is expected to increase by approximately 6% (Shah et al., 2004) with no additional energy use. Den Hond (2007) estimates alumina yield to increase by 6-10 g/L. The decrease in energy consumption due to the higher alumina yield is depicted in Table 3-6. The investment cost is estimated at $8/tonne alumina (based on den Hond et al., 2007).

Tube digestion with indirect preheating (2). Replacing autoclaves with tube digesters will result in a significant decrease in energy use and CO_2 emissions. With indirect heating, the direct injection of steam in the bauxite slurry is avoided, resulting in more efficient utilization of steam in other parts of the process and reduced energy use for evaporation. Energy savings will depend on the initial energy use and may range from 3 GJ/tonne alumina to up to 5.7 GJ/tonne alumina (Kunwar, 2011; Suss et al., 2004). Switching from steam injection digestion to tube digestion will require the complete re-design and rebuilt of the digester (IPTS/EC, 2013). The investment cost for an integrated digestion and evaporation facility employing jacket pipe heaters is estimated at $36-$97/tonne alumina (based on HATCH, 2011).

High rate thickening technology (3). After sand separation, if required, the digestion discharge slurry passes through decanters for the separation of mud and green liquor. With the use of high-rate decanters, the liquor-to-mud contact time is reduced, reducing the reversion effect in which un-extracted bauxite in mud acts as seed for premature gibbsite crystallization. Alumina yield can improve by 1-2 g/L at an investment cost of 6$/tonne alumina. (den Hond et al., 2007)

Seed filtration (4). The introduction of seed filters drastically reduces the recycle of spent liquor, increases the precipitation fill A/C ratio, and the agglomeration capacity of fines. Alumina yield can increase by 5-10 g/L at an investment cost of $14/tonne alumina (den Hond et al., 2007).

Inter-stage cooling (5). The introduction of as much as five inter-stage cooling steps will result in a closer to the optimum precipitation process. Alumina yield will increase by 2-5 g/L at an investment cost of $5/tonne alumina. (den Hond et al., 2007)

Direct cooling (6). In the heat interchange department (HID), green liquor going to precipitation is cooled by exchanging heat with the spent liquor leaving the precipitation and heading to digestion. Replacing indirect cooling using flash steam by direct cooling (i.e. heat exchangers), can enable digestion at higher caustic concentration and hence result in increased alumina yield. Alumina yield will increase by about 1-3 g/L at an investment cost of $4/tonne alumina. (den Hond et al., 2007)

Stationary calciners (7). Fluidized bed calcination (FBC) employs preheating and cooling with the use of several cyclone stages offering improved energy efficiency compared to rotary kilns (Missalla et al., 2011). Replacing rotary kilns with fluidized bed calciners will result in about 30% energy savings (Missalla et al., 2011; Klett et al., 2011). Currently, all new plants prefer stationary calciners, such as circulating fluidized bed calciners or flash calciners. In 1995, 66% of alumina was calcined in FBCs (IEA GHG, 2000). Currently, the share of alumina produced in stationary calciners to the overall alumina production has increased to 80% (Williams and Schmidt, 2012). The investment cost is estimated at $43/tonne alumina (based on IEA GHG, 2000).

Optimized cyclone operation (8). Cyclones are widely used in the calcination of alumina for cooling and preheating. By improving the separation efficiency, fewer fines recirculate, resulting in improved heat recovery and lower pressure losses. Energy use for calcination can be reduced by 6% (Dena, 2010). The investment cost is estimated at $0.1/tonne alumina (based on Dena, 2010).

"Hydrate by-pass" system (9). With the installation of a hydrate by-pass system, a part of alumina hydrate (up to 15%) can "by-pass" the calciner and enter a pot where it is calcined by the hot alumina leaving the calciner. In this way a part of alumina hydrate is directly calcined by the increased temperature of the produced alumina. Energy use will decrease by 3-5% (Missalla et al., 2011). Information on the required investment cost could not be found. It is assumed that the investment cost required is half the cost required for the "improved waste heat recovery" measure; $3.3/tonne alumina.

Improved waste heat recovery (10). Waste heat recovery in a stationary kiln employing several cyclone stages and a hydrate by-pass system can be further improved. For example, heat from the cooler can be used to dry moist hydrate prior to its entrance to the first preheating stage. As the drying heat requirements are now lower, more preheater stages could be added to utilize heat form the calciner off-gases. Energy savings for a calciner already utilizing a hydrate by-pass system are estimated at 3% (Klett et al., 2011). The investment cost is estimated at $6.5/tonne alumina.

Improved process control (11). The Bayer process is composed of highly interactive processes with long dead times. Advanced control of the whole alumina refining process will result in increased yield throughput and lower energy use. Fuel use due to improved efficiency and higher throughput is estimated to decrease by 5% while electricity use is also expected to decrease by the same amount. Investment costs are estimated at $3/tonne alumina (based on Sidrak, 2001).

Switch from the alternative processes to the Bayer process (low temperature digestion) (12). Importing better quality bauxite in countries such as China and Russia would eliminate the use of the more energy intensive Combined Bayer-Sinter, Sinter, Bayer-Flotation and Lime-Bayer processes. Replacing the Sinter process would decrease the energy use by 27 GJ/tonne alumina (based on energy use of 38 GJ/t for the Sinter process and 10 GJ/t for the Bayer process with low temperature digestion). Replacing the Combined Bayer-Sinter process with the Bayer, will reduce the energy use by about 16 GJ/tonne alumina; alumina production with the Combined Bayer-Sinter process consumes in Russia about 27 GJ/t alumina (Liu et al., 2010) and in China about 26 GJ/t alumina (Li et al., 2008).

The investment costs for switching from the Combined Bayer-Sinter to the Bayer process will amount to $100/tonne while operational costs (excluding the impact of lower energy use) are expected to increase by about $60/tonne alumina, primarily due to the increased costs from importing better quality bauxite and the additional caustic soda requirements. Switching from the Sinter to the Bayer process will require an investment of $170/tonne alumina. Although bauxite and caustic soda consumption will increase, operational costs (excl. energy use) are expected to decrease by about $110/tonne alumina due to lower limestone requirements and the elimination of soda ash needs.

In addition, replacing the Bayer-Flotation and Lime-Bayer processes with the Bayer process will require an investment of about $20/tonne alumina. Switching from the Bayer-Flotation to the Bayer process will decrease operational costs (excl. energy use) by $10/tonne alumina as improved material use will more than compensate the increased bauxite costs. Switching from the Bayer-Flotation to the Bayer process will lower operational costs by $110/tonne alumina mainly due to the lower limestone use.

Switch from the alternative processes to the Flotation-Bayer (13). When better quality bauxite cannot be obtained, the combined and the Sinter processes could potentially be replaced by a less energy intensive process that composes a variation of the Bayer process; the Flotation-Bayer process. Energy use could decrease by about 10 GJ/tonne when replacing the Combined Bayer-Sinter process and by 22 GJ/tonne when replacing the Sinter process (for an energy use of the Bayer-Flotation process of 16 GJ/tonne).

When replacing the Combined Bayer-Sinter process, the investment costs required will amount to $160/tonne alumina while operational cost are expected to increase by about $75/tonne alumina due to increased bauxite and caustic soda costs. For the replacement of the Sinter process the investment costs will be about $230/tonne while operational costs are expected to decrease by about $105/tonne due to elimination of soda ash.

Table 3-6 Energy efficiency improvements for alumina refining[1]

No	Measures	Electricity Savings (kWh/tonne alumina)	Fuel Savings (GJ/tonne alumina)	Investment Costs ($/tonne alumina)	Change in O&M costs ($/tonne alumina)[2]	Technical lifetime (years)
	Digestion					
1	Sweetening	N/A	0.9	8	N/A	20
2	Tube digestion + indirect heating	-	4.4	66	N/A	20
	Clarification					
3	High rate thickeners - HT Plants	N/A	0.2	6	N/A	20
	High rate thickeners - LT Plants	N/A	0.15	6	N/A	20
	Precipitation					
4	Seed filtration - HT Plants	N/A	0.9	14	N/A	20
	Seed filtration - LT Plants	N/A	0.7	14	N/A	20
5	Inter-stage cooling - HT Plants	N/A	0.4	5	N/A	20
	Inter-stage cooling - LT Plants	N/A	0.35	5	N/A	20
	Heat Interchange					
6	Direct cooling – HT Plants	N/A	0.3	4	N/A	20
	Direct cooling – LT Plants	N/A	0.2	4	N/A	20
	Calcination					
7	Kiln retrofit	-	1.4	43	N/A	20
8	Optimized cyclone operation	3	0.2	0.1	N/A	20
9	"Hydrate-by-pass" system	-	0.1	3.3	N/A	20
10	Improved waste heat recovery	-	0.1	6.5	N/A	20
	Overall process					
11	Advanced process control	14	0.6	3.0	N/A	10
12	Combined Bayer-Sinter→ Bayer-flotation	N/A	10.4	160	+75	20
	Sinter→ Bayer-flotation	N/A	22.0	230	-105	20
13	Combined Bayer-Sinter→ Bayer	N/A	16.0	100	+60	20
	Sinter→ Bayer	N/A	27.0	170	-110	20

Bayer-flotation, Lime-Bayer→ Bayer[3]	N/A	5.0	20	-60	20

[1] The energy savings each measure can achieve, and the associated investment costs presented in this study are only indicative. The actual energy efficiency improvements and investment costs are site-specific and should be carefully assessed prior to implementation.

[2] These values exclude the change in energy costs. This is to avoid double counting when using Equations 3-1 and 3-2.

[3] Since no information could be retrieved regarding the share of the Bayer-Flotation and the Lime-Bayer process on the overall Chinese alumina production, for this energy efficiency improvement measure we use the average investment and operational costs reported in the above paragraphs.

Aluminium smelting

Conversion to PFPB technology cells (13). The conversion of the CWPB, SWPB and the outdated Söderberg cells to state-of-the-art PFPB technology will have major energy and environmental benefits. Upgraded PFPB plants have an energy use of 13.8 MWh/tonne while greenfield PFPB plants are characterized by an even lower energy use of 13.4 MWh/tonne aluminium (Schwarz et al., 2001). The energy savings will depend on the technology substituted and will range from about 5-20% while PFC emissions can decrease by up to 93% (see Table 3-4). The investment cost required will range from $260-620 for switching from SWPB and CWPB to PFPB cells. For switching from the Söderberg technology cells to PFPB the investment is substantial estimated at $2,600/tonne aluminium (see Table 3-7) (Harnisch et al., 1998)[33].

Optimize cell operation (14). With the further improvement of pot control and point-feeding systems in existing PFPB cells, the occurrence of anode effects can be reduced, while the electrolytic bath will be better controlled resulting in more optimal operating conditions (BCS, 2007). The electricity use can decrease by about 0.2 MWh/tonne aluminium, while the investment cost will range between 100 and 150 Euros/tonne aluminium (Schwarz, 2008). It is common, when such cell renovations are conducted, to also increase the cell amperage and anode size and implement new cathodes (Morrey, 2001 as found in Schwarz, 2008). Due to the lack of data on investments to renovate PFPB cells, we assume investment costs twice the investment cost reported by Schwartz et al. (2008) for optimizing pot control. The renovation of current PBPB cells can decrease the electricity use by 15%.

Anode production and ingot casting

Energy consumption for anode manufacture and ingot casting can be reduced with the improvement of the process heating systems i.e. through the optimization of the combustion process, heat containment, heat transfer, waste heat recovery and improved process control (U.S. DOE, 2004). The associated investment costs of energy efficiency improvements were estimated based on the average payback period (PBP) reported in the Industrial Assessment Centers (IAC) Database for all U.S. manufacturing industries and the typical energy costs. As the PBP depends on energy prices and the U.S. natural gas prices have experienced great fluctuation within the period 2000-2013, in the case of heat savings the average PBP of a specific year was taken into consideration and not the average PBP of all years.

Optimum combustion air flow (15). The efficiency of the combustion process can increase with the use of the optimum amount of excess air, resulting in the use of the appropriate air-to-fuel ratio. The energy savings range between 5 and 25% (U.S. DOE, 2004). For an average PBP of 0.9 years reported for 2011 (IAC, 2013) in U.S. industries and 15% average energy savings, the investment cost is estimated at $2-3 per tonne aluminum ingot.

Adjust burners for efficient operation (16). The use of proper burners can increase the amount of heat transferred to the load increasing productivity and reducing fuel requirements.

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[33] In this study, to adjust the investment costs from older years to current years, we used the Chemical Engineering Plant Cost Index (CEPCI).

Improving heat transfer in furnaces will result in 5-10% energy savings (U.S. DOE, 2004). For an average PBP of 1 year reported for 2011 (IAC, 2013) in U.S. industries and 8% average energy savings, the investment cost is estimated at $1.6-2.0 per tonne aluminum ingot.

Furnace pressure control (17). Fixing the leaks and installing or correctly operating pressure control will result in 5-10% energy savings (U.S. DOE, 2004). In this way, heat losses due to air infiltration often observed when furnaces are operated at negative pressures can be avoided. For an average PBP of 0.9 years reported for 2011 (IAC, 2013) in U.S. industries and 8% average energy savings, the investment cost is estimated at $1.4-1.8 per tonne aluminum ingot.

Use insulation in furnaces to facilitate heating/cooling (18). The use of insulating materials reduces heat losses to the environment through convection and conduction. The energy savings are in the range of 2-5% (U.S. DOE, 2004). For an average PBP of 0.3 years reported for 2009 (IAC, 2013) in U.S. industries and 4% average energy savings, the investment cost is estimated at $0.4-0.6 per tonne aluminum ingot.

Use waste heat from hot flue gases to preheat combustion air (19). With the recovery of the heat of exhaust gases to preheat the combustion air, the heat losses decrease while also less fuel is required to reach the necessary process temperature. The energy savings range between 10 and 30% (U.S. DOE, 2004). For an average of 1.7 years for 2009 (IAC, 2013) and 20% average energy savings, investment is estimated at $8-12/tonne aluminium ingot.

Improved sensor and control systems (20). Control systems can be improved to reduce energy losses especially when the system operates at low throughput (U.S. DOE, 2004). Energy savings are estimated at 5-10% with a typical PBP of 0.1-0.5 years (Thekdi, 2000). The investment cost is estimated at $0.2-1.0 per tonne aluminum ingot.

Machine driving systems

Optimized operation of motor systems (21). According to the IAI survey (2013a), in 2010, about 15.6 MWh/tonne were needed to produce 1 tonne of aluminium. About 15.3 MWh/tonne aluminium (98% of overall electricity use) were consumed in electrolysis and the remaining in alumina refining, anode production and ingot casting. Less than 7% of the electricity used in electrolysis, about 1 MWh/tonne of aluminum (IAI, 2013c; Covec, 2009), is used in auxiliary equipment and rectifiers. Rectification losses account for about 2% of electricity use (Covec, 2009).

Based on the 2010 Manufacturing Energy Consumption Survey (MECS) (EIA, 2013c), in 2010, about 60% of the electricity consumed in other than the electrochemical process in the U.S. primary aluminium industry, was used for machine drives. Energy use in motor systems can be reduced by 15% through motor upgrading and system level efficiency measures, i.e. correct motor sizing, employ ASDs, improve the energy efficiency of pump, fan and air compressor systems (U.S. DOE, 2002). Hence, we estimate that energy efficiency improvements for machine driving equipment can decrease electricity use by about 0.1 MWh/tonne aluminium. The investment cost is estimated based on the average PBP of 1.1 years for all U.S. industries as reported in the IAC (2013) at $7/tonne aluminum.

Table 3-7 Energy efficiency improvements for aluminium smelting, anode production and ingot casting[1]

No	Measures	Electricity Savings (MWh/tonne aluminium)	Fuel Savings (%)	Fuel Savings (GJ/tonne aluminium)	Investment Cost ($/tonne aluminium)	Technical lifetime (years)
	Aluminium smelting					
13	VSS → PFPB	2.8	-	-	2,600	20
	HSS → PFPB	2.8	-	-	2,600	20
	SWPB → PFPB	0.8	-	-	620	20
	CWPB → PFPB	1.7	-	-	260	20
14	Optimize cell operation	2.0	-	-	240-410	20
	Anode production and ingot casting[2]					
15	Optimum combustion air flow	-	5-25%	0.2-0.8	2.2-3.0	10
16	Efficient operation of burners	-	5-10%	0.2-0.3	1.6-2.0	10
17	Furnace pressure control	-	5-10%	0.2-0.3	1.4-1.8	10
18	Furnace insulation	-	2-5%	0.1-0.2	0.4-0.6	10
19	Waste heat recovery	-	10-30%	0.3-1.0	8-12	20
20	Sensor and control systems	-	5-10%	0.2-0.3	0.2-1.0	10
	Motor driving equipment[3]					
21	Optimized motor system operation	0.1	-	-	7	10

[1] The energy savings each measure can achieve, and the associated investment costs presented in this study are only indicative. The actual energy efficiency improvements and investment costs are site-specific and should be carefully assessed prior to implementation.

[2] The energy savings for anode production and ingot casting are estimated based on the average energy use for anode production and ingot casting reported in the IAI data survey (IAI, 2013a) and in BCS (2007).

[3] The electricity savings from improvements in motor systems also take into account electricity use in alumina refineries.

3.5 Results and discussion

Figure 3-4 depicts the energy use and GHG emissions under the frozen efficiency and the business-as-usual scenarios and the energy use when all energy savings measures identified in this study are applied without taking economic considerations into account ("technical"), and the energy use when only cost-effective measures are adopted ("cost-effective") under the frozen efficiency scenario.

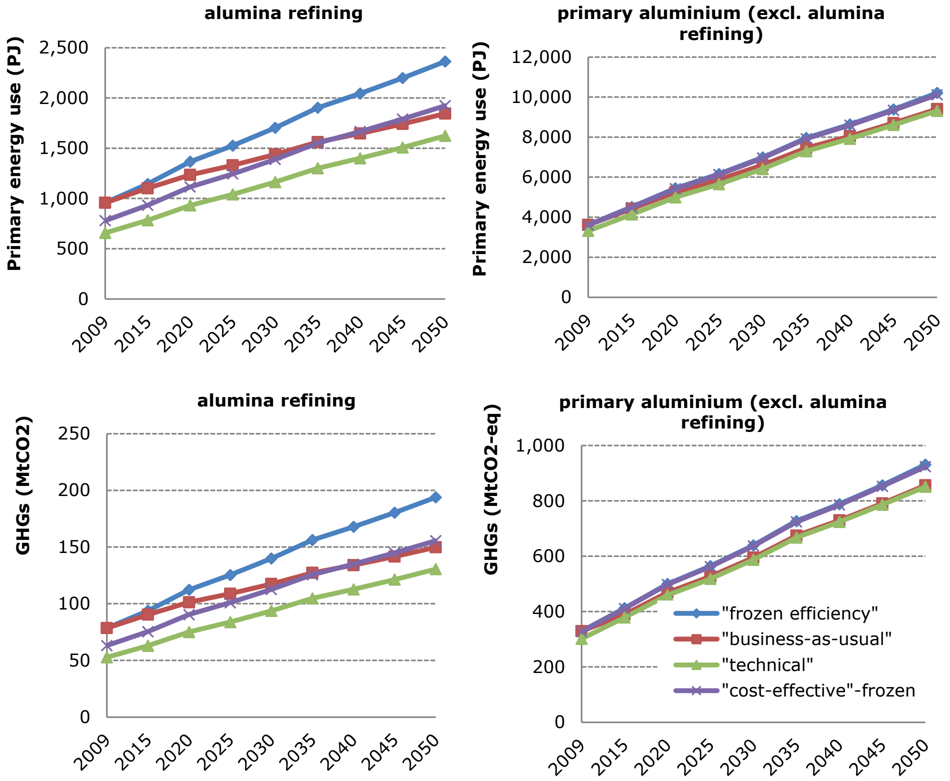

Figure 3-4 Energy use and GHG emission development under different scenarios (discount rate = 30%)

Under the frozen efficiency scenario, the primary energy use in alumina refining (top 6 alumina producing countries) will increase from 957 PJ in 2009 to about 2,360 PJ in 2050; an increase of 147%. Similarly, GHG emissions from alumina refining, primarily from fuel combustion, will increase from about 80 $MtCO_2$ in 2009 to 194 $MtCO_2$ in 2050. Under the business-as-usual scenario the increase in both primary energy use and GHG emissions is less drastic with primary energy use and GHG emissions reaching about 1,845 PJ and 150 $MtCO_2$ by 2050, respectively. There is the technical potential to limit the energy use by 31% when compared to the frozen efficiency scenario and 12% when compared to the business-as-usual scenario. The cost-effective potential for reducing the energy and GHG emissions is estimated at 19% and 20% when compared to the frozen efficiency scenario, respectively.

The primary energy use for primary aluminium production (excl. alumina refining) (top 11 primary aluminium producing countries) under the frozen efficiency scenario is expected to increase from about 3,600 PJ in 2009 to 10,200 PJ in 2050; an increase of more than 180%. The GHG emissions will show a similar increase, increasing from about 330 $MtCO_{2\text{-eq}}$ in 2009 to 930 $MtCO_{2\text{-eq}}$ in 2050. In the business-as-usual scenario, the increase in energy use remains substantial; the 2050 primary energy use is estimated at 9,400 PJ and the GHG emissions at 856 $MtCO_{2\text{-eq}}$. The technical potential for reducing the primary energy use and GHG emissions is 9% when compared to the frozen efficiency scenario, while when in comparison to the business-as-usual scenario, the remaining technical potential is low, estimated at 0.9% and 0.6%, respectively. The cost-effective primary energy and GHG savings potential when in comparison to the frozen efficiency scenario is 0.9% and 0.8%, respectively.

Cost-supply curves

Figure 3-5 shows the cost-supply curves for alumina refining under the frozen efficiency and the business-as-usual scenarios. As shown in more detail in Table 3-8, 10 out of the 18 energy efficiency improvement measures are cost-effective, as their CCE is less than zero.

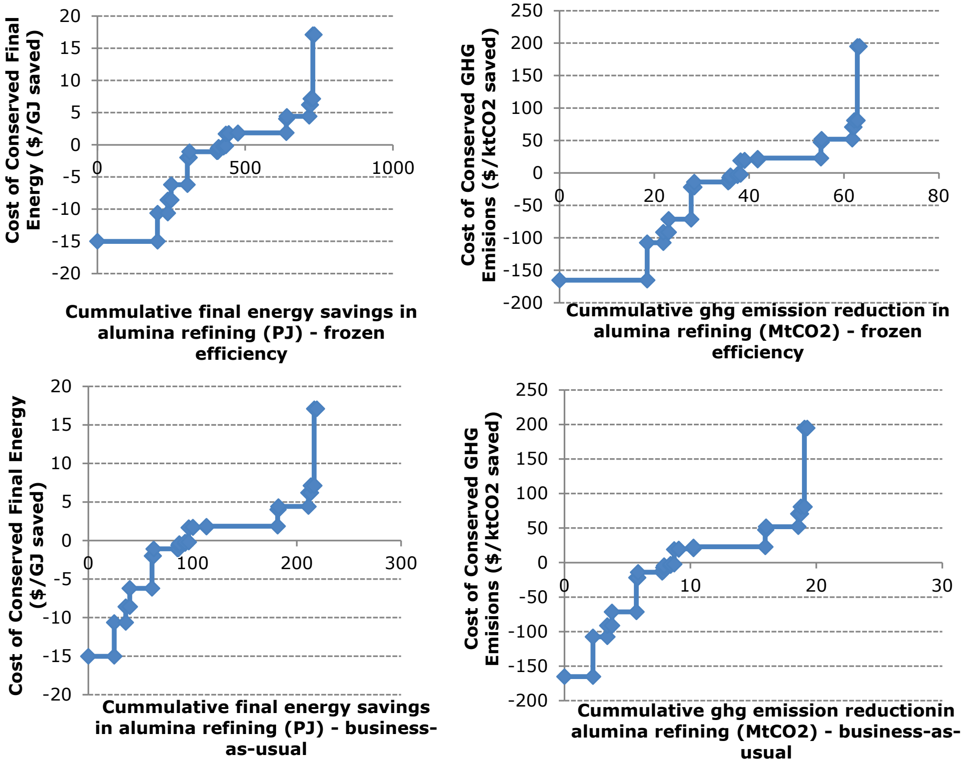

Figure 3-5 Energy and GHG abatement curves for the alumina refining industry (year 2050; discount rate=30%)

Table 3-8 shows all the energy efficiency improvement measures for alumina refining assessed in this study, along with their contribution to the total technical and cost-effective energy and GHG savings potentials. Under the frozen efficiency scenario, the cost-effective energy and GHG savings potential is 435 PJ (59% of the technical potential) and about 38 $MtCO_2$, respectively. Measures with the highest impact are the replacement of alternative options for alumina refining that currently operate in China and Russia, tube digestion and kiln retrofitting. Assuming that China and Russia can obtain better quality bauxite and therefore adopt the Bayer process, about 422 PJ and 115 PJ could be saved under the frozen efficiency and the business-as-usual scenarios, respectively.

The energy savings potentials under the business-as-usual are lower as new capacities installed have already adopted the measures and old capacity improved annually by 0.4%. To account for the improvement in old stock, it is assumed that the measures with the lowest CCE in each country have been adopted. Under the business-as-usual scenario it is assumed that all new alumina capacity installed in China and Russia uses the Bayer process.

In practice, the cost-effectiveness of the measures does not only depend on the change in energy expenditures. For example, all measures that improve the alumina refineries' yield, when adopted for capacity purposes, will lower the refinery's fixed costs and increase certain process efficiencies. These measures, even if they may not be justifiable based only on their energy conserving capabilities, from an overall economics point of view, they might be cost-effective.

To assess the potential for energy savings under a scenario in which Russia and China keep on processing local bauxite with a lower than the average bauxite quality, the efficiency measures "*Combined Bayer-Sinter→Bayer*" and the "*Sinter→Bayer*" are replaced by the "*Combined Bayer-Sinter→Flotation-Bayer*" and the "*Sinter→Flotation Bayer*", while the measure "*Bayer-Flotation, Lime-Bayer→Bayer*" is not taken into consideration. In this scenario, the total technical potential for energy savings under the frozen-efficiency and the business-as-usual scenarios are 463 PJ and 94 PJ, respectively. For more information on the absolute energy savings and the cost-effectiveness of each measure in this scenario see Figure 3-8 and Table 3-25 in Appendix 3A.

Table 3-8 Energy efficiency measures for the alumina refining industry ranked based on their CCE$_{\text{-final}}$ (discount rate=30%)

Efficiency measures	"frozen-efficiency"			"business-as-usual"			Associated costs	
	final energy savings (PJ)	primary energy savings (PJ)	GHG emissions savings (MtCO2)	final energy savings (PJ)	primary energy savings (PJ)	GHG emissions savings (MtCO2)	Cost of conserving final energy ($/GJ)	Cost of mitigating GHGs ($/ktCO2)
Bayer-flotation, Lime-Bayer → Bayer	203	203	18.5	25	25	2.3	-15.0	-165
Advanced control	35	39	3.4	11	13	1.1	-10.6	-107
Optimized cyclone operation	12	13	1.1	4	4	0.4	-8.6	-91
Sinter → Bayer	55	55	4.7	21	21	1.9	-6.2	-71
Sweetening	7	7	0.6	2	2	0.1	-2.0	-22
Tube digestion+indirect heating	93	93	7.1	23	24	1.9	-1.1	-14
Inter-stage cooling - HT Plants	3	3	0.3	1	1	0.1	-1.1	-13
Direct cooling - HT Plants	3	3	0.2	1	1	0.1	-0.6	-7
Inter-stage cooling - LT Plants	17	17	1.5	6	6	0.5	-0.4	-4
Seed filtration - HT Plants	8	8	0.6	3	3	0.3	-0.2	-2
Total “cost-effective”	435	440	38.2	96	99	8.7		
Direct cooling - LT Plants	10	10	0.8	4	4	0.4	1.7	19
Seed filtration - LT Plants	31	31	2.8	13	13	1.2	1.8	20
Combined Bayer-Sinter → Bayer	164	164	13.3	68	68	5.7	1.9	23
High rate thickeners - HT Plants	2	2	0.1	1	1	0.1	4.0	47
Kiln retrofit	76	76	6.5	29	29	2.6	4.4	52
"Hydrate-by-pass" system	5	5	0.4	2	2	0.2	6.2	71
High rate thickeners - LT Plants	7	7	0.6	3	3	0.3	7.1	81
Improved waste heat recovery	5	5	0.4	3	3	0.2	17.1	195
Total “technical”	734	740	63.3	219	222	19.3		

Figure 3-6 shows the energy and GHG abatement curves for the primary aluminium industry (excluding alumina refining). Under the frozen efficiency scenario, most of the measures are identified as non cost-effective measures (CCE higher than the cost of purchasing energy). As in the business-as-usual scenario it is assumed that Söderberg cells will be phased out by 2050, these measures do not contribute to the energy savings potential.

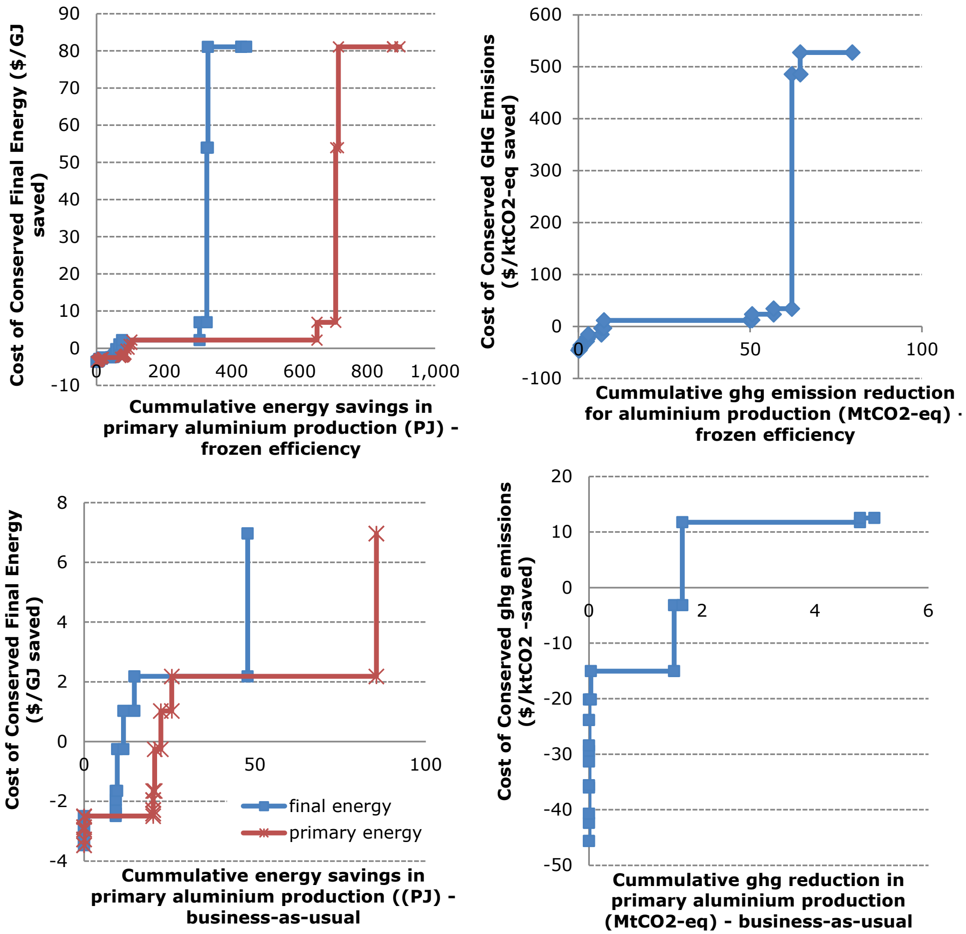

Figure 3-6 Energy and GHG abatement curves for the primary aluminium industry (year 2050; excluding alumina refineries) (discount rate=30%)

Table 3-9 presents the contribution of each measure to the overall savings potential. Under the frozen efficiency scenario, about 896 PJ of primary energy can be saved. Under the business-as-usual scenario however, the energy savings potential is significantly lower, as most of the energy savings potential identified in the frozen efficiency scenario has been implemented. This is primarily due to the assumptions used for the construction of the business-as-usual scenario; the phasing out of Söderberg cells by 2050, the adoption of all energy efficiency measures in new installed aluminium capacity and the 0.2% energy efficiency improvement in old capacity. About 15% of the final energy savings, 11% of the primary energy savings and 9% of the GHG emissions savings is cost-effective under the frozen efficiency scenario, while under the business-as-usual scenario the percentages increase to 24%, 26% and 33% respectively.

The technical potential would have been higher if innovative measures were also taken into consideration. New technologies currently being researched such as wetted drained cathodes and inert anodes can substantially improve the efficiency of the Hall-Héroult process, while other new technologies such as carbothermic reduction and kaolinite reduction can be used to replace the Héroult process.

Table 3-9 Energy efficiency measures for the primary aluminium production ranked based on their CCE$_{\text{-final}}$ (discount rate=30%)

Efficiency measures	"frozen-efficiency"			"business-as-usual"			Associated costs	
	final energy savings (PJ)	primary energy savings (PJ)	GHG emissions savings (MtCO2)	final energy savings (PJ)	primary energy savings (PJ)	GHG emissions savings	Cost of conserving final energy	Cost of mitigating GHGs ($/ktCO2)
Sensor and control systems_ingot	3.5	3.5	0.3	0.0	0.0	0.0	-3.7	-46
Sensor and control systems_anodes	3.0	3.0	0.2	0.0	0.0	0.0	-3.5	-42
Furnace insulation_ingot	1.6	1.6	0.1	0.0	0.0	0.0	-3.3	-41
Furnace insulation_anodes	1.4	1.4	0.1	0.0	0.0	0.0	-2.9	-36
Optimum combustion air flow_ingot	7.0	7.0	0.6	0.0	0.0	0.0	-2.9	-36
Furnace pressure control_ingot	3.5	3.5	0.3	0.0	0.0	0.0	-2.5	-31
Optimize motor system operation	22.9	51.6	3.8	9.3	20.2	1.5	-2.5	-15
Optimum combustion air flow_anodes	6.0	6.0	0.5	0.0	0.0	0.0	-2.4	-29
Efficient operation of burners_ingot	3.5	3.5	0.3	0.0	0.0	0.0	-2.3	-28
Furnace pressure control_anodes	3.0	3.0	0.2	0.0	0.0	0.0	-2.0	-24
Efficient operation of burners_anodes	3.0	3.0	0.2	0.4	0.4	0.0	-1.7	-20
Waste heat recovery_ingot	9.4	9.4	0.8	1.8	1.8	0.1	-0.3	-3
Total “cost-effective”	67.8	96.5	7.4	11.5	22.5	1.7		
Waste heat recovery_anodes	8.0	8.0	0.7	3.2	3.2	0.3	1.0	13
Optimized cell operation	228.8	546.8	42.5	33.2	59.9	3.1	2.2	12
CWPB →PFPB	21.2	55.2	6.3	0.0	0.0	0.0	7.0	24
SWPB → PFPB	3.4	8.1	5.3	0.0	0.0	0.0	54.0	34
VSS → PFPB	98.5	159.8	15.1	0.0	0.0	0.0	81.1	528
HSS → PFPB	14.6	21.9	2.4	0.0	0.0	0.0	81.1	486
Total “technical”	442.2	896.2	79.7	47.9	85.5	5.0		

In Table 3-10 and Table 3-11 can be seen the energy savings and GHG savings potentials identified in the top 6 alumina and top 11 primary aluminium producing countries. Notice, that the total cost-effective savings potentials appearing in Table 3-10 and Table 3-11 differ from the total cost-effective savings potentials in Table 3-8 and Table 3-9. This is because the CCE shown in Table 3-8 and Table 3-9 is the weighted average CCE. However, due to different energy prices, the CCE will be different in each country and measures that might be cost-effective in one country might not be cost-effective in another.

Table 3-10 Energy and GHG savings potentials in alumina refining per country (discount rate=30%)

Countries	2050 alumina production (Mtonnes)	Final energy savings (PJ)				GHG savings (MtCO2)			
		frozen efficiency		BAU		frozen efficiency		BAU	
		cost-effective	technical	cost-effective	technical	cost-effective	technical	cost-effective	technical
China	56	285	527	64	178	26.3	48.2	5.9	16.3
Russia	4	10	83	0	25	0.7	5.6	0.0	1.7
Australia	50	54	64	0	1	3.8	4.6	0.0	0.1
United States	3	15	16	8	9	0.8	0.9	0.4	0.5
India	8	21	32	2	7	2.0	3.0	0.2	0.7
Brazil	22	5	12	0	0	0.4	0.9	0.0	0.0
Total	143	390	734	73	219	34.0	63.3	6.6	19.3

The highest potential for energy savings in the alumina refining industry appears in China and Russia, 83% of technical energy savings potential, as these two countries currently use energy intensive alternative to the Bayer processes to produce alumina. China alone accounts for 72% of the technical energy savings potential under the frozen efficiency scenario due to its large alumina production and the high energy savings potential there is from switching to the Bayer process. However, if China and Russia keep processing local bauxite, the switch from the alternative alumina refining processes to the Bayer-flotation process instead of the switch to the Bayer process will lower the technical potential for energy savings to 281 PJ in China and 58 PJ in Russia.

Table 3-11 Energy and GHG savings potentials for primary aluminium production (excl. alumina refining) per country (discount rate=30%)

Countries	2050 primary aluminium production (Mtonnes)	Final energy savings (PJ)				Primary energy savings (PJ)				GHG savings (MtCO$_{2\text{-eq}}$)			
		frozen efficiency		BAU		frozen efficiency		BAU		frozen efficiency		BAU	
		cost-effective	technical	cost-effective	technical	cost-effective	technical	cost-effective	technical	cost-effective	technical	cost-effective	technical
China	34	134	139	7	9	331	339	17	19	30.2	33.3	1.6	1.7
Russia	10	3	69	0	8	3	92	0	12	0.2	7.1	0.0	0.1
Australia	3	2	31	0	5	2	77	0	11	0.2	8.2	0.0	1.0
United States	3	3	22	1	7	4	44	1	16	0.2	4.0	0.1	1.2
India	13	11	77	1	4	15	168	1	8	1.2	14.8	0.1	0.6
Brazil	4	2	32	0	1	2	34	0	1	0.2	1.9	0.0	0.0
Canada	6	3	32	0	11	3	32	0	11	0.2	1.6	0.0	0.0
Norway	2	1	2	0	1	1	2	0	1	0.1	0.2	0.0	0.0
United Arab Emirates	3	0	12	0	1	0	34	0	1	0.0	2.1	0.0	0.1
Bahrain	2	0	10	0	0	0	30	0	1	0.0	1.9	0.0	0.1
South Africa	3	1	16	0	1	1	44	0	4	0.1	4.6	0.0	0.4
Total	83	160	442	9	48	363	896	21	86	33	80	1.8	5.0

The highest potential for energy savings in the primary aluminium industry (excluding alumina refining) under the frozen efficiency scenario appears in China, 31% of the total technical energy savings potential and then follows India with 17%. Improvements in primary aluminium production can decrease total GHG emissions by 80 MtCO$_{2\text{-eq}}$, 80% of which can take place in China, Russia, India, and Australia.

Technologies that are found cost-effective across all countries are “advanced control” and “optimized cyclone operation” while almost all measures concerning improvements in anode baking and ingot casting are also considered cost-effective. In the case of aluminium smelting and for a 30% discount rate, all measures are found to be non-cost effective in all countries except in China, the country with the highest electricity prices, where “optimized cell operation” is found to be cost-effective.

It is important to note that in this analysis, the adoption of energy efficiency measures in countries that use electricity produced from renewable sources (e.g. hydropower) for aluminium smelting such as Brazil, Canada and Norway, will not result in as high primary energy and GHG savings as in countries producing electricity from fossil fuels. [34]

For a number of countries that use large amounts of hydropower for aluminium smelting, using the average country mix for the generation of electricity will result in higher primary energy savings and GHG abatement potential (see Table 3-26 in Appendix 3A) than the potentials shown in Table 3-11. Using the average country fuel mix for electricity generation will result in about 1,100 PJ total primary energy savings and 97 $MtCO_{2-eq}$ - emission reduction potentials under the frozen efficiency scenario.

Sensitivity Analysis

To assess the cost-effective potentials presented above, we performed a sensitivity analysis and calculated the cost-supply curves for varying discount rates and energy prices.

In energy models, the discount rate can be used to demonstrate the hurdles to adopting energy efficiency measures. In this analysis, a high discount rate of 30% is used. By decreasing the discount rate, the CCE of each energy efficiency measure decreases, increasing the cost-effective savings potential. The opposite happens when the discount rate increases, limiting in this way the cost-effective savings potential. Figure 3-7 shows the energy conservation curves for different discount rates.

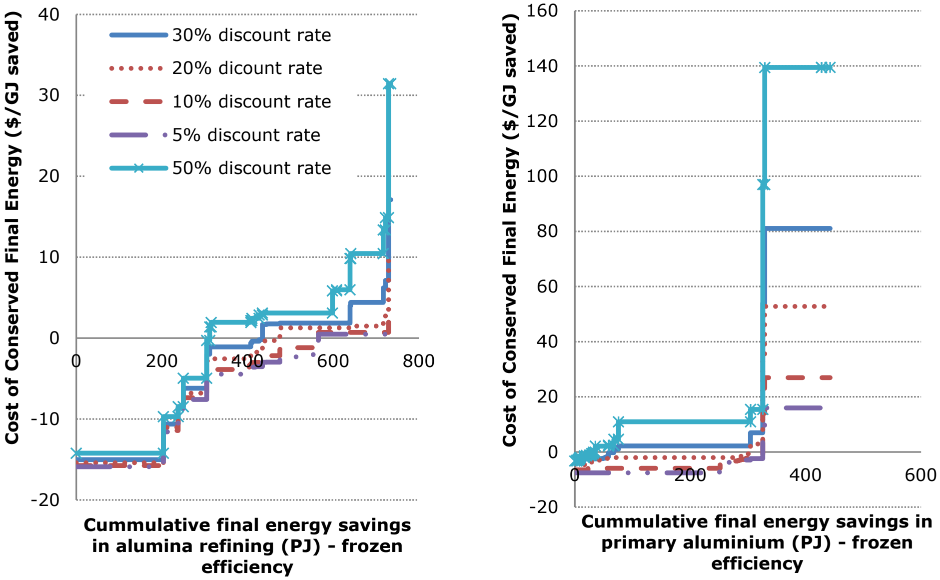

Figure 3-7 Energy abatement curves for the alumina refining and the primary aluminium (excluding alumina refineries) industries for varying discount rates

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[34] Although in this analysis we have considered a near-zero emission factor for hydropower for every country, in reality, GHG emissions can vary substantially per country as tropical reservoirs were shown to be non-negligible GHG emitters (1,300-3,000 $kgCO_{2-eq}/MWh$) (Steinhurst et al., 2012).

The use of a lower discount rate will decrease the CCE of each measure shifting the cost-supply curves vertically downwards as shown in Figure 3-7. Table 3-12 shows the impact of a lower and a higher discount rate on the cost-effective energy savings potentials.

Table 3-12 Cost-effective final energy savings potentials under the frozen efficiency scenario for varying discount rates

discount rates	alumina refining			primary aluminium (excl. alumina refining)		
	cost-effective (PJ)	non-cost-effective (PJ)	share of cost-effective on the overall technical potential	cost-effective (PJ)	non-cost-effective (PJ)	share of cost-effective on the overall technical potential
50%	312	423	42%	36	384	8%
30%	435	300	59%	68	374	15%
20%	475	259	65%	305	138	69%
10%	565	169	77%	326	116	74%
5%	565	169	77%	326	116	74%

In this analysis, the energy prices used in the calculations were assumed to remain stable through the years. The fluctuation however of energy prices, will affect the cost-effectiveness of every energy efficiency improvement measure.

Table 3-13 shows the cost-effective savings potentials for higher and lower energy prices while maintaining all other parameters such as the discount rate and the investment costs stable. It is shown, that for 30% higher energy prices there will be a significant increase in the cost-effective energy savings potentials in primary aluminium production with the measure "*Improved pot control and cathode design*" becoming cost-effective. On the other hand, a decrease in energy prices can substantially decrease the cost-effectiveness of measures. For example, a decrease in energy prices by 15% and 30% will decrease the cost-effective energy savings potential for the alumina refining industry by 6% and 28%, respectively.

Table 3-13 Cost-effective final energy savings potentials under the frozen efficiency scenario for varying energy prices

Change in energy prices	alumina refining			primary aluminium (excl. alumina refining)		
	cost-effective (PJ)	non-cost-effective (PJ)	share of cost-effective on the overall technical potential	cost-effective (PJ)	non-cost-effective (PJ)	share of cost-effective on the overall technical potential
+50%	639	95	87%	305	138	69%
+30%	435	300	59%	305	138	69%
+15%	435	300	59%	68	374	15%
current prices	435	300	59%	68	374	15%
-15%	408	326	56%	58	384	13%
-30%	312	423	42%	36	384	8%
-50%	305	430	41%	30	390	7%

Another parameter that can highly influence the cost-effectiveness of the measures is the investment cost of the technologies. A higher future investment cost will decrease the identified cost-effective energy savings potentials while the opposite is true for lower future investment costs. In this analysis, the investment costs were assumed to remain constant throughout the 2009-2050 period as it is hard to estimate whether capital costs will increase due to for example higher inflation rates or go down due to a high learning-rate.

3.6 Conclusion and recommendations

In this paper we identified available measures to reduce the energy use and greenhouse gas emissions in the primary aluminium industry up to 2050, and constructed energy and GHG abatement curves to assess the technical and cost-effective energy and GHG savings potentials.

This study estimates that there is a technical potential to decrease the 2050 energy use in alumina refining by 31% under the frozen efficiency scenario and by 12% under the business-as-usual scenario. The technical potential to decrease CO_2 emissions is identified at 33% under the frozen efficiency scenario and 13% under the business-as-usual scenario.

The wide adoption of energy efficiency improvement measures in primary aluminium production (excluding alumina refining) has the technical potential to decrease the primary energy use by 9% under the frozen efficiency scenario. In the business-as-usual scenario the technical potential (including only currently available technologies) is limited to 0.9%.

When compared to Kermeli et al. (2013), the energy savings potentials under the business-as-usual identified in this study are lower. There are two main reasons that can explain this difference: a) in this analysis and under the business-as-usual scenario, it was assumed that all new capacity installed in China and Russia adopts the energy efficient Bayer process limiting therefore the future energy savings potential, and b) in this analysis, only the adoption of currently available measures was taken into consideration.

Concluding, this study identified that under a frozen efficiency scenario the 2050 primary energy use in the primary aluminium industry can be lowered by 1,636 PJ, equivalent to 13% of the 2050 primary energy use; 740 PJ in alumina refining and 896 PJ in primary aluminium production (excl. alumina refining). Under a business-as-usual scenario the 2050 technical primary energy savings potential is 307 PJ equivalent to about 3% of the 2050 primary energy use; 222 PJ in alumina refining and 86 PJ in primary aluminium production (excluding alumina refining).

In the frozen efficiency scenario, the countries with the highest primary energy savings potential are China (57%), Russia (13%), Australia (8%) and India (8%). For China and Russia to achieve these high energy savings potentials better quality bauxite needs to be used. In a scenario in which China and Russia keep on processing local low-quality bauxite, the energy savings breakdown per country is different; China (46%), Russia (14%), Australia (11%) and India (11%). In the business-as-usual scenario the countries with the highest primary energy savings potential are China (70%), Russia (12%) and the United States (6%).

The aim of this study was to identify the currently available energy efficiency measures that can play a significant role in mitigating GHG emissions in the primary aluminium industry and determine the cost of the investments required, assisting in this way policy makers to better understand the potentials for energy and GHG savings in this sector and construct effective and efficient industry specific policies. It was identified that the highest energy savings potentials in the primary aluminium industry from the widespread BPT adoption exists in the alumina refining industry. Concerning the smelting of aluminum, if no new technologies will become available in the coming years there will only be a small potential for energy efficiency improvement and GHG emission reduction. To further reduce GHG emissions beyond energy efficiency, investments in RD&D in new technologies will need to be made, and the decarbonization of the power sector will need to be promoted.

This analysis could be strengthened with the use of more country specific data regarding energy consumption such as the energy use for alumina refining in Brazil and Russia and country specific data regarding the energy use in less energy intensive processes such as anode manufacture and ingot casting. More information regarding the energy efficiency improvement of the different energy saving measures and the change their implementation would have in the overall plant operation and maintenance costs. In addition, more information concerning the lifetime and retirement of equipment would allow to more explicitly model stock turnover. Furthermore, country specific data on technology penetration levels would strengthen the implementation rates estimated for each measure. Areas in which further research could contribute into a better estimation of the future cost-efficient potentials are the development of future investment costs required for implementing the different technologies and the development of energy prices in each country. The inclusion of more measures such as efficient transformers in aluminium smelter facilities and cogeneration in alumina refineries and the inclusion of innovative measures that are likely to become commercially available in the future, could increase the future energy and GHG savings potentials identified in this analysis.

Appendix 3A

Table 3-14 Estimated shares of metallurgical alumina production and capacity utilization rates (based on regional data found in IAI, 1013b)

Countries	2009 share of metallurgical alumina production on the total alumina production	2009 capacity utilization rates
China	96%	87%
Australia	98%	100%
Brazil	99%	91%
India	86%	83%
Russia	92%	94%
United States	83%	61%
World	94%	87%

Table 3-15 Default CO_2 emission factors per fuel (IPCC, 2006a)

Fuel type	tonnes CO_2/TJ
Residual fuel oil	77.4
Coal (anthracite)	98.3
Natural gas	56.1
Biofuels	0[1]

[1] As biofuels are considered a renewable energy source, we use a zero CO_2 emission factor.

Table 3-16 Fuel use breakdown in 2009 (based on IEA 2011a)

Countries	coal	oil	natural gas	biofuels and waste[1]	heat	other	total
China	76%	10%	3%	0%	11%	0%	100%
Russia[2]	14%	16%	30%	0%	40%	0%	100%
Canada	0%	1%	99%	0%	0%	0%	100%
United States	0%	7%	91%	0%	2%	0%	100%
Australia	26%	19%	53%	0%	0%	0%	100%
Brazil	7%	68%	25%	0%	0%	0%	100%
Norway	0%	47%	53%	0%	1%	0%	100%
India	71%	29%	0%	0%	0%	0%	100%
United Arab Emirates[2]	0%	4%	96%	0%	0%	0%	100%
Bahrain	0%	0%	100%	0%	0%	0%	100%
South Africa[2]	89%	11%	0%	0%	0%	0%	100%

[1] According to the IAI statistics (2013c), most of the fuel used in alumina refining is coal, gas and oil. Thus, for this analysis we set the share of biomass and waste on the overall fuel use to 0%.

[2] Due to non-reliable data concerning the fuel use in the non-ferrous metals industry in Russia, United Arab Emirates and South Africa, instead of the of the fuel mix breakdown in the non-ferrous metals industry, the fuel mix breakdown of the overall industrial sector is used.

Table 3-17 Fuel mix for the generation of electricity used in alumina refineries (based on IEA 2011a)

Countries	coal	oil	natural gas	nuclear	hydro	geothermal	Solar/wind /other	Biofuels and waste
Australia	78%	1%	14%	0%	5%	0%	2%	1%
United States	45%	1%	23%	20%	7%	0%	2%	2%
Canada	15%	1%	6%	15%	60%	0%	1%	1%
Norway	0%	0%	3%	0%	96%	0%	1%	0%
Bahrain	0%	0%	100%	0%	0%	0%	0%	0%
Brazil	2%	3%	3%	3%	84%	0%	0%	5%
China	79%	0%	2%	2%	16%	0%	1%	0%
India	69%	3%	12%	2%	12%	0%	2%	0%
Russia	17%	2%	47%	17%	18%	0%	0%	0%
South Africa	94%	0%	0%	5%	1%	0%	0%	0%
United Arab Emirates	0%	2%	98%	0%	0%	0%	0%	0%
World	40%	5%	21%	13%	16%	0%	2%	1%

Table 3-18 Fuel mix for the generation of electricity used in aluminium smelters, anode production and ingot casting facilities

Countries	coal	oil	natural gas	nuclear	hydro	geothermal	Solar/wind/ other	Biofuels and waste	Total
Australia	75%	1%	13%	0%	8%[1]	0%	2%	1%	100%
United States[2]	58%	0%	1%	1%	39%	0%	0%	0%	100%
Canada	0%	0%	0%	0%	100%[3]	0%	0%	0%	100%
Norway	0%	0%	2%	0%	98%[4]	0%	0%	0%	100%
Bahrain	0%	0%	100%[5]	0%	0%	0%	0%	0%	100%
Brazil	1%	2%	2%	2%	90%[6]	0%	0%	3%	100%
China[7]	85%	0%	2%	2%	10%	0%	1%	0%	100%
India	39%	2%	7%	1%	50%[8]	0%	1%	0%	100%
Russia	3%	0%	9%	3%	84%[9]	0%	0%	0%	100%
South Africa[10]	94%	0%	0%	5%	1%	0%	0%	0%	100%
United Arab Emirates	0%	2%	98%[11]	0%	0%	0%	0%	0%	100%
World[12]	51%	0%	8%	2%	38%	0%	0%	0%	100%

[1] USGS, 1998; Turton, 2002.

[2] Green, 2007.

[3] USGS, 1998; also, according to own estimations based on CIEEDAC (2012) hydropower for aluminium smelting in Canada accounts for more than 97% of the electricity used.

[4] NVE, 2009.

[5] USGS, 1998.

[6] EPE, 2013.

[7] IAI, 2013c.

[8] Bhushan, 2010.

[9] USGS, 1998; Gurov, 2003.

[10] Due to the lack of data for South Africa, the same fuel mix as in Table **3-17** is used.

[11] USGS, 1998; DUBAL, 2010.

[12] IAI 2013c.

Table 3-19 Electricity conversion efficiency[1] (based on IEA 2011a)

Countries	coal	oil	natural gas	nuclear	hydro	geothermal	Solar/wind/other	Biofuels and waste
Australia	35%	36%	39%	--	100%	--	100%	15%
United States	37%	40%	48%	33%	100%	18%	99%	33%
Canada	42%	29%	40%	33%	100%	--	100%	38%
Norway	38%	N/A	56%	--	100%	--	101%	34%
Bahrain	--	--	30%	--	--	--	--	--
Brazil	32%	39%	46%	33%	100%	--	100%	47%
China	34%	35%	40%	33%	100%	10%	100%	25%
India	27%	21%	41%	33%	100%	--	100%	15%
Russia	32%	30%	33%	33%	100%	10%		25%
South Africa	34%	35%	--	33%	100%	--	91%	25%
United Arab Emirates	--	25%	32%	--		--	--	--
World	35%	40%	42%	33%	100%	10%	102%	31%

[1] The method used to determine the conversion efficiencies per fuel type in each country was the "power loss factor" method (see Graus and Worrell, 2011). A correction factor of 0.18 and 0.22 was used for public heat and auto-producers, respectively, to account for the electricity that would have been generated in case no heat was produced (Graus and Worrell, 2011).

Table 3-20 GDP growth rates (2009-2035 based on regional growth rates reported in IEA (2011c) and 2035-2050: Graus and Kermeli (2012))

Countries	2009-2020	2020-2035	2035-2050	2009-2050
China	8.17%	4.24%	2.70%	4.69%
Russia	4.19%	3.34%	1.80%	3.00%
Canada	3.33%	2.47%	1.20%	2.23%
Australia	3.22%	2.00%	0.70%	1.85%
USA	2.57%	2.20%	1.10%	1.89%
India	7.62%	5.82%	3.10%	5.30%
Brazil	4.37%	3.16%	2.60%	3.27%
Norway	2.13%	1.84%	1.00%	1.61%
United Arab Emirates	4.27%	3.75%	2.80%	3.54%
Bahrain	4.27%	3.75%	2.80%	3.54%
South Africa	4.49%	4.40%	4.20%	4.36%
World	4.20%	3.18%	2.20%	3.08%

Table 3-21 Estimated current energy savings potentials in alumina refining per country

Countries	Current (GJ/tonne)	BPT (Low-T) (GJ/tonne)	BPT (High-T)[1] (GJ/tonne)	BPT (average)[2] (GJ/tonne)	Energy savings potential
China[3]	19.4	9.0	10.0	9.1	-53%
Australia	10.5	9.0	10.0	9.2	-12%
Brazil	9.6	9.0	10.0	9.0	-6%
India	14.4	9.0	10.0	9.2	-36%
Russia[3]	27.9	9.0	10.0	9.0	-67%
United States	14.4	9.0	10.0	9.9	-32%

[1] The HT BPT is based on the energy use at the Yarwun (formerly Comalco) alumina refinery in Australia. The Yarwun refinery processes boehmitic bauxite at high temperature with tube digestion and has an energy use of less than 10 GJ/t alumina (Rio Tinto Alcan, 2010).

[2] Based on the shares of high and low temperature digestion in each country (see Table 3-22).

[3] In the case of China and Russia the energy savings potentials are based on the assumption that China and Russia have access to better quality bauxite and all alumina refineries use the Bayer process.

Table 3-22 Shares of high temperature and low temperature digestion

Countries	High-temperature digestion	Low-temperature digestion
China	60%	40%
Australia	24%	76%
Brazil	0%	100%
India	15%	85%
United States	85%	15%
Russia	60%	40%

Table 3-23 Estimated implementation rates[1]- alumina refining - frozen efficiency scenario

No.	Measures	China	Australia	Brazil	India	Russia	United States
	Digestion						
1	Sweetening – HT Plants[2]	7%	0%	0%	5%	0%	0%
2	Tube digestion + Indirect heating – HT Plants[3]	13%	20%	0%	15%	0%	85%
	Clarification						
3	Install high rate thickeners - High Temp Plants	9%	2%	0%	15%	0%	26%
	Install high rate thickeners - Low Temp Plants	61%	8%	10%	85%	20%	5%
	Precipitation						
4	Implement seed filtration - HT Plants	9%	2%	0%	15%	0%	26%
	Implement seed filtration - LT Plants	61%	8%	10%	85%	20%	5%
5	Implement inter-stage cooling - HT Plants	9%	2%	0%	15%	0%	26%
	Implement inter-stage cooling - LT Plants	61%	8%	10%	85%	20%	5%
	Heat Interchange						
6	Direct cooling - HT Plants	9%	2%	0%	15%	0%	26%
	Direct cooling - LT Plants	61%	8%	10%	85%	20%	5%
	Calcination						
7	Kiln retrofit	66%[4]	12%[5]	20%[6]	17%[7]	89%[8]	20%[6]
8	Optimize cyclone operation	70%	10%	10%	100%	20%	30%
9	Install a "hydrate-by-pass" system[9]	70%	10%	10%	100%	20%	30%
10	Improve waste heat recovery	70%	10%	10%	100%	20%	30%
	Overall Process						
11	Advanced control	70%	10%	15%	100%	20%	30%
12	Combined Bayer-Sinter→ Bayer-Flotation, Lime-Bayer	11%	0%	0%	0%	92%	0%
	Sinter→ Bayer-Flotation, Lime-Bayer	3%	0%	0%	0%	8%	0%
13	Combined Bayer-Sinter→ Bayer-LT	11%	0%	0%	0%	92%	0%
	Sinter → Bayer-LT	3%	0%	0%	0%	8%	0%
	Bayer-Flotation, Lime-Bayer Process→ Bayer-LT	73%	0%	0%	0%	0%	0%

[1] Author own estimations. When no information is available the implementation rates are based on the energy savings potentials from wide BPT adoption (see Table 3-21).

[2] Sweetening can only be implemented on high temperature digestion (see Table 3-22). As this measure has already been implemented in many countries (IAI, 2013a), the implementation rate is significantly lower that the share of high temperature digestion.

[3] Tube digestion has only been adopted in two alumina refineries (IPTS/EC, 2013); the Rio Tinto Alcan Yarwun (formerly known as Comalco) alumina refinery (1.4 mtpa) in Australia (responsible for about 7% of Australian alumina production in 2009) (Rio Tinto Alcan, 2010), and one refinery in Germany (IPTS/EC, 2013; Hudson et al., 2005). Thus, the implementation rate for this technology for every country in this study is equal to the share of high temperature digestion (see Table 3-22). Exceptions are i) Australia for which the implementation rate is lowered by 7%, ii) China where due to the inclusion of measures "Combined Bayer-Sinter→ Bayer", "Sinter→Bayer" and "Bayer-Flotation, Lime-Bayer→ Bayer" the majority of alumina is produced with the low temperature Bayer process and iii) Russia where again due to the inclusion of the process switch measures no alumina will be produced with high temperature Bayer process.

[4] According to Wind and Raahauge (2013), most plants built in China after 2005 employ gas suspension calciners. Chinese alumina capacity increased from 18.5 Mtonnes in 2005 to 28 Mt in 2009 (USGS, 2007a, 2007b, 2010a, 2010b, 2011). Thus, in 2009, at least 34% of alumina capacity uses stationary calciners.

[5] Author own estimations based on available capacity and technology information (AAC, 2013; NTEPA, 2004; Williams and Schmidt, 2012; Alcoa, 2007; Wind and Raahauge, 2013; Alcoa, 2005; Outotec, 2011).

[6] Due to the lack of information assumed equal to the world average (20%) (Williams and Schmidt, 2012).

[7] Author own estimations based on available capacity and technology information (EMT-India, 2004; PIB, 2003; Ministry on environment and forests, 2008; Hindalco, 2004; Hindalco, 2013).

[8] Author own estimation based on capacity and technology information found in UC RUSAL (2010).

[9] Hydrate by-pass was developed in the 1990s and is installed in 6 plants worldwide (Klett et al., 2011). Thus, for this study we assume a high implementation rate.

Table 3-24 Estimated implementation rates - aluminium smelting - frozen efficiency scenario

Measures	China[1]	Russia[2]	Canada[3]	Australia[4]	United States[5]	India[6]	Brazil[7]	Norway[3]	United Arab Emirates[3]	Bahrain[3]	South Africa[3]
VSS → PFPB[8]	0%	52%	22%	0%	17%	19%	39%	0%	0%	0%	12%
HSS → PFPB[8]	0%	13%	2%	0%	1%	1%	3%	0%	0%	0%	1%
SWPB → PFPB[8]	2%	1%	1%	0%	1%	1%	1%	2%	2%	2%	2%
CWPB →PFPB[8]	0%	1%	0%	100%	0%	0%	0%	0%	0%	0%	0%
Optimized cell operation[9]	40%	10%	30%	25%	60%	40%	40%	0%	40%	40%	40%

[1] According to Gao et al. (2009), all Chinese smelters use the prebake technology.

[2] UC Rusal, 2010.

[3] Since no more recent data could be retrieved, the USGS (1998) data for 2003 are used.

[4] According to the Commonwealth Government Initiative (2000) all primary aluminum production in the late 90s in Australia took place in CWPB cells.

[5] According to Green (2007) in 2005, 82% of U.S. primary aluminium was produced in prebake cells.

[6] According to Bhushan (2010) in 2003, 80% of primary aluminium capacity used the prebake technology.

[7] According to CNI (2012) in 2010, 58% of primary aluminium capacity used the prebake technology.

[8] Specific information on the type of Söderberg and prebake technologies used could only be retrieved for Australia and Russia. For the remaining countries, the implementation rates are estimated based on world ratios. For prebake technology (non-Australia) that is 98% PFPB, 0% CWPB and 2% SWPB. For Söderberg technology (non-Russia) that is 93% VSS and 7% HSS.

[9] Due to the lack of information the implementation rates for this measure were estimated based on the energy savings potential from BPT adoption.

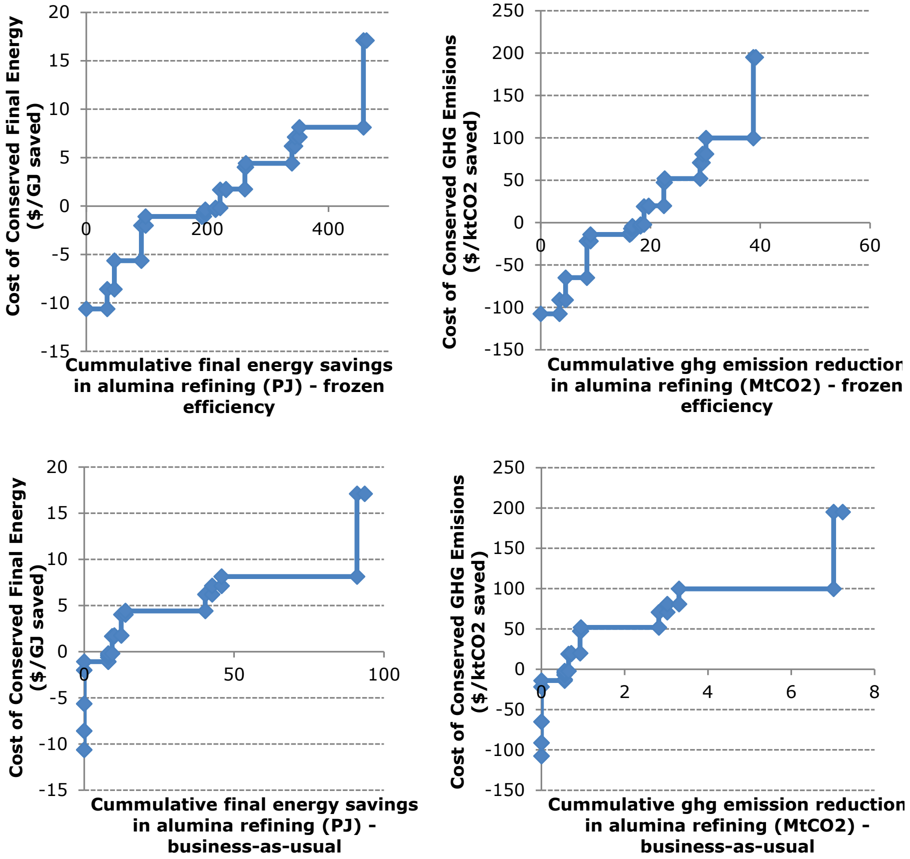

Figure 3-8 Energy and GHG abatement curves for the alumina refining industry (discount rate=30%)-(switch alternative processes used in China & Russia to the Bayer-flotation instead of the Bayer)

Table 3-25 Energy efficiency measures for the alumina refining industry ranked based on their CCE$_{\text{-final}}$ (discount rate=30%)-(switch alternative processes used in China & Russia to the Bayer-flotation instead of the Bayer)

Efficiency measures	"frozen-efficiency"			"business-as-usual"			Associated costs	
	final energy savings (PJ)	primary energy savings (PJ)	GHG emissions savings (MtCO2)	final energy savings (PJ)	primary energy savings (PJ)	GHG emissions savings (MtCO2)	Cost of conservin g energy ($/GJ)	Cost of mitigating GHGs ($/ktCO2)
Advanced control	35	39	3.4	0	0	0.0	-10.6	-107
Optimized cyclone operation	12	13	1.1	0	0	0.0	-8.6	-91
Sinter --> Bayer-flotation	45	45	3.9	0	0	0.0	-5.6	-65
Sweetening	7	7	0.6	0	0	0.0	-2.0	-22
Tube digestion+indirect heating	93	93	7.1	8	9	0.6	-1.1	-14
Inter-stage cooling - HT Plants	3	3	0.3	0	0	0.0	-1.1	-13
Direct cooling - HT Plants	3	3	0.2	0	0	0.0	-0.6	-7
Inter-stage cooling - LT Plants	17	17	1.5	0	0	0.0	-0.4	-4
Seed filtration - HT Plants	8	8	0.6	1	1	0.1	-0.2	-2
Total “cost-effective”	221	227	18.8	9	10	0.7		
Direct cooling - HT Plants	10	10	0.8	1	1	0.1	1.7	19
Seed filtration - LT Plants	31	31	2.8	2	5	0.2	1.8	20
High rate thickeners - HT Plants	2	2	0.1	1	1	0.0	4.0	47
Kiln retrofit	76	76	6.5	27	27	1.9	4.4	52
"Hydrate-by-pass" system	5	5	0.4	2	2	0.2	6.2	71
High rate thickeners - LT Plants	7	7	0.6	3	3	0.3	7.1	81
Combined Bayer-Sinter --> Bayer-flotation	106	106	8.6	45	45	3.7	8.1	100
Improved waste heat recovery	5	5	0.4	3	3	0.2	17.1	195
Total “technical”	463	468	39.2	94	96	7.2		

Table 3-26 Energy and GHG savings potentials for primary aluminium production (excl. alumina refining) per country

Countries	2050 primary aluminium production (Mtonnes)	Final energy savings (PJ)				Primary energy savings (PJ)[1]				GHG savings (MtCO2-eq)[1]			
		frozen efficiency		BAU		frozen efficiency		BAU		frozen efficiency		BAU	
		cost-effective	technical	cost-effective	technical	cost-effective	technical	cost-effective	technical	cost-effective	technical	cost-effective	technical
China	34	134	139	7	9	317	325	17	18	28.1	31.3	1.5	1.6
Russia	10	3	69	0	8	3	195	0	28	0.2	15.6	0.0	1.4
Australia	3	2	31	0	5	2	81	0	12	0.2	8.4	0.0	1.0
United States	3	3	22	1	7	4	54	2	19	0.2	3.8	0.1	1.2
India	13	11	77	1	4	19	238	2	12	1.7	23.6	0.1	1.0
Brazil	4	2	32	0	1	2	39	0	2	0.2	2.1	0.0	0.0
Canada	6	3	32	0	11	3	52	0	19	0.2	3.0	0.0	0.5
Norway	2	1	2	0	1	1	2	0	1	0.1	0.2	0.0	0.0
United Arab Emirates	3	0	12	0	1	0	34	0	1	0.0	2.1	0.0	0.1
Bahrain	2	0	10	0	0	0	30	0	1	0.0	1.9	0.0	0.1
South Africa	3	1	16	0	1	1	44	0	4	0.1	4.6	0.0	0.4
Total	83	160	442	9	48	353	1093	21	117	30.9	96.7	1.8	7.3

[1] The fuel mix for electricity generation is the country average based on IEA (2011a) (see Table 3-17).

Part 2:

Capturing key industrial characteristics in log-term energy models for improved modeling results

4 Comparing projections of industrial energy demand and greenhouse gas emissions in long-term energy models [35]

Abstract

The industry sector consumes 37% of the global final energy use and currently emits more GHG emissions than any other end-use sector. Effective mitigation strategies needed to reach a climate target will require a significant reduction of industrial emissions. In long-term energy models, which are used to identify strategies to mitigate emissions, the industry sector representation thus plays a crucial role. To improve our understanding of the variation in the projected industrial pathways, in this study, a comparison of the models key input and structure assumptions in relation to the modelled sectors' mitigation potential is performed. All models show similar trends in a reference scenario (i.e., absent emissions mitigation policies), with strong decoupling of final energy use to GDP growth in Non-OECD countries and the sector remaining mostly (>50%) reliant on fossil energy through 2100. Even so, industrial final energy demand spans a wide range (between 203-451 EJ/yr) across the models. There is significant divergence in the projected ability to switch to alternative fuels to mitigate GHG emissions. Among the set analyzed here, the more technologically detailed models tend to have less capacity for switching from fossil fuels to electricity. This highlights the importance of understanding of economy-wide mitigation responses and costs as an area for future improvement. Analyzing industry subsector material and energy use details can improve the ability to interpret results and provide insight in feasibility emission reduction measures.

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[35] Based on: Edelenbosch, O.Y, K. Kermeli, W. Crijns-Graus, E. Worrell, R. Bibas, B. Fais, S. Fujimori, P. Kyle, F. Sano, and D.P. van Vuuren. (2017). Comparing projections of industrial energy demand and greenhouse gas emissions in long-term energy models. *Energy* 122, 701-710.

4.1 Introduction

In 2010, 37% of global final energy consumption was used by industrial activities (IEA, 2012a). Moreover, annual industrial greenhouse gas (GHG) and waste/wastewater emissions increased from 13.0 to 15.4 $GtCO_2eq$ between 2005 and 2010, emitting more GHGs than any other end-use sector[36] (IPCC, 2014b). While global industrial energy intensity decreased within the past years due to the adoption of energy and material efficiency measures and due to efficient capacity increases in developing countries, the increasing demand for industrial products and the shift towards more energy intensive industrial products (structural changes) have resulted in an increase in global industrial energy use (UNIDO, 2011). The International Energy Agency (IEA) projects that if current trends continue, the industrial energy use could more than double from 126 EJ[37] in 2009 to 250-270 EJ in 2050 (IEA, 2012b). For the same period, the associated GHG emissions are projected to increase by 45 to 56%. Effective climate change policies will thus need to be adopted in the industry sector to reach stringent climate targets (IPCC, 2014b).

Integrated Assessment Models (IAMs) have been frequently used to analyze the potentials for reaching climate targets by identifying strategies of emission reduction and associated investment costs. The strength of IAMs lies in analyzing tradeoffs and synergies in mitigation across different sectors (IPCC, 2014a), projecting future anthropogenic emissions of energy production, energy conversion, energy consumption and land use change. Following the identification of the industrial sector as a large energy consumer and GHG emitter, it is clear that industry representation plays an important role in these models scenarios.

Including sector specifics at the global level running over the coming decades, which is the scope in which many IAMs operate, is a modelling challenge however (Krey, 2014). End-use sectors are highly diverse, characterized by different energy functions and a large variety in technologies affecting the demand for energy (Sugiyama et al., 2014). This is particularly true for the industrial sector, where energy is used in many different industrial processes to manufacture a wide variety of products[38] (Liu & Ang, 2007; OECD, 2011). Where traditionally end-use sectors in most IAMs were represented in a stylized manner, over the last years, many models have started to include more sector details.

The IPCC Fifth Assessment report shows that there is a broad range in the estimated development of industrial emissions over the century, across the different integrated studies (IPCC, 2014a). To design effective mitigation policies, accurate estimations on emission reduction potentials and the associated investments are needed. Therefore, understanding the origins of the variation in model outcomes, by identifying the robust and uncertain features in

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[36] The total energy demand is usually broken down into four end-use sectors: industry, transport, buildings and agriculture, forestry and other land use (AFOLU).

[37] This figure includes energy use as a feedstock, energy use in blast furnaces and coke ovens (own energy use and transformation energy) and excludes energy use in refineries.

[38] In this paper the term industry is used for all activities contributing to the production of goods and construction of building and infrastructure. Main industrial products are iron & steel, non-metallic minerals, chemicals & petrochemicals, pulp & paper, non-ferrous metals and other products.

the projected pathways, is of great importance (Kriegler et al., 2015). Over the last few years, many model comparison studies have been published which looked at the behaviour of IAMs. A few studies focussed on the energy and land-use systems as a whole, such as (van der Zwaan et al., 2013) comparing technology diffusion, (Kriegler et al., 2014) on the role of low carbon technologies for energy transformation; (Calvin et al., 2012) comparing regional projections; and (Rosen & Guenther, 2015) exploring mitigation costs, while others have targeted a specific sector (such as the transport sector (Girod et al., 2013)) or specific forms of renewable energy (such as bio-energy (Calvin et al., 2013)).

A limited number of studies however, have specifically dealt with the modelling of the industrial sector. Zhang et al. (2015), investigated the advantages and weaknesses in the methods used for modelling the Chinese industry in nineteen energy models; including bottom-up, top-down, hybrid, global vs national and industrial level models. They identify key issues to be the modelling technology options, change, cost, and diffusion, emphasize that modelling technological change is vital for realistic industrial energy projections. Moreover, non-linearities such as in market saturation effects as well structural change and synergies between energy use climate change and air pollution mitigation pose large challenges to industrial modelling. Sathaye (Sathaye, 2011), performed a review of the technology representation in seven energy models that specifically model the cement industry and highlighted the importance of the inclusion of bottom-up details for more accurate cost estimations.

Recognizing the industrial sector complexities and the importance of understanding “between model” uncertainties, we conduct a detailed comparison of the industrial sector representation within models that use an *integrated* strategy to reach a global GHG reduction target. Model output is compared to model input and structure assumptions to better understand the similarities and differences in model behaviour. In addition, we take a detailed look into one major industrial subsector - the cement industry - in terms of global energy consumption and emission generation to assess the more detailed sub-sector representation of some models.

The article is structured as follows. In Section 4.2, the method applied to compare the industry model assumptions and outputs is discussed. In the following Section (Section 4.3) we provide an overview of the industry sector representation in models. Then, in Section 4.4 the model projections for two scenarios are presented, i.e. i) a “baseline scenario” where current trends continue and significant improvements beyond business-as-usual in energy intensity are not considered and ii) a mitigation scenario, where CO_2 emissions are mitigated and concentration levels stay below 450 ppm (“450 ppm scenario”). In Section 4.5, specific attention is given to the modelling of the cement industry. Finally, in Section 4.6 presents the discussion and conclusions paragraphs.

4.2 Method

The models included in the study can be classified as IAMs and energy system models which together will be called long-term energy models. IAMs describe the interaction between the human system and the natural environment, i.e. climate change, energy use and land-use. Energy system models are models that focus on the energy system, from the extraction of primary energy to its use in the final end use sectors.

4.2.1 Model structure and assumption comparison

To better understand how the industrial sector is modelled, a descriptive questionnaire that addresses the assumptions made in the models structure, system boundaries, energy and material demand drivers, technology change and policy measures has been constructed and filled in by all participating models. The questionnaire results are discussed in Section 4.3 and presented in more detail in Appendix 4A.

4.2.2 Scenario description

To compare the industrial sector projections of the models, key industrial model outputs of *two scenarios* were collected:

- one scenario without new climate policies ("baseline scenario") and,
- one scenario aiming at a stabilization level at 450 ppm CO_2-eq ("mitigation scenario").

The modeling results were collected under the EU-FP7 ADVANCE project. For some models, MESSAGE, GCAM and Imaclim-R, that did not provide modeling results under the EU-FP7 ADVANCE, the results from another study under the Energy Modeling Forum (Kriegler et al., 2014) were used.

Models were asked to provide a medium-growth baseline but no attempt was made to harmonize assumptions – thus taking different demographic and economy growth rates as part of the overall uncertainty (see Section 4.3.2). The baseline scenario is compared to the *current policy scenario* of the IEA's World Energy Outlook (WEO), that takes into account those policies and measures affecting energy markets and were formally enacted as of mid-2013. The mitigation scenario is compared to the WEO *450 scenario*, which stabilizes at around 450 ppm CO_2-eq in 2100 as well (IEA, 2013).

The model drivers, global population and GDP are depicted in Figure 4-1. For reference, the WEO scenario is shown as well. In the WEO scenario global GDP (expressed in real purchasing power parity [PPP] terms) is projected to continue to grow between 2011 and 2035 at an average annual rate of 3.6%, doubling in size over this period. Population, a fundamental driver of energy demand, grows from 7.0 billion in 2011 to 8.5 billion in 2035 (IEA, 2013). Most models scenario drivers stay relatively close to these assumptions in the coming decades and start to diverge after 2035.

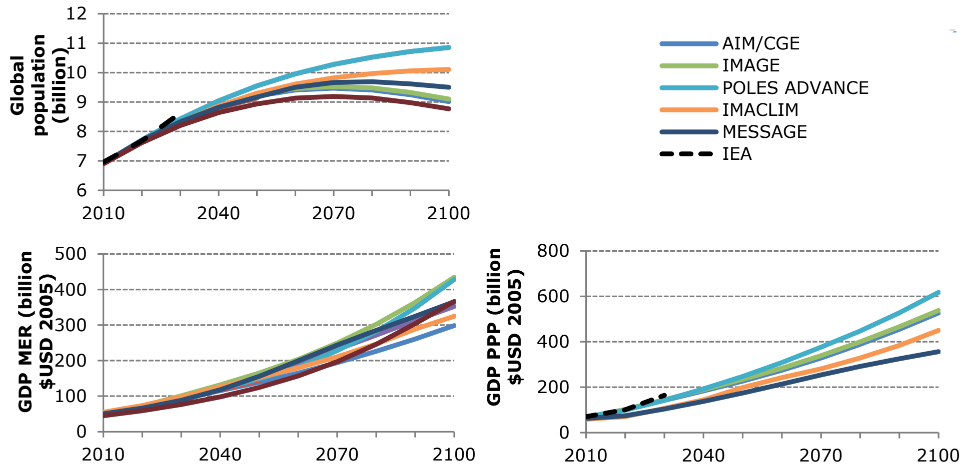

Figure 4-1 Scenario drivers: a) Global Population; b) GDP expressed in Market Exchange Rates; c) GDP expressed in real purchasing power terms.

4.3 Description of the industry sector in global energy system models

4.3.1 Model characteristics

Eight models[39] participated in this study, that are widely used in IPCC assessment reports, namely: AIM-CGE, DNE21+, GCAM, Imaclim-R, IMAGE, MESSAGE, POLES and TIAM-UCL. The models are briefly introduced in Table 4-1 in terms of their general characteristics.

Table 4-1 General characteristics of the models studied

	AIM-CGE	DNE-21+	GCAM	Imaclim-R	IMAGE	MESSAGE	POLES	TIAM-UCL
Type of model	CGE	Energy system model	Hybrid/ IAM	CGE with bottom-up modules for every sector	Hybrid/ IAM	IAM based on bottom-up energy model	Energy system model	IAM based on bottom-up energy model
Solution type	Simulation	Optimization	Simulation	Simulation	Simulation	Optimization	Simulation	Optimization
Number of regions	17	54	14	12	24	11	57	16

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[39] All models presented here are part of the European Union Seventh Framework Programme FP7/2007-2013 ADVANCE project

Although the distinction is not always clear, energy models are commonly categorized based on their disaggregation level into top-down and bottom-up models. Bottom-up models have a relatively high amount of technological detail. Most of the ‘bottom-up’ models are energy-system models focusing on the behavior of the energy system. Top-down models, with less technological details model the economy by taking into account interactions between the various sectors (e.g. the interaction between the energy sector and the rest of the economy). Most top-down models are Computable Generic Equilibrium (CGE) models, representing the sectoral economic activities by production functions (Löschel, 2002). Another key difference across the models is the solution type used. This study includes optimization models, i.e. an algorithm is used to optimize a distinct target (depending on model type mostly maximizing consumption or minimize energy system costs) across a period of time, as well as simulation models, that run based on a set of rules that determine the decisions made in every single time-period based on the information from the previous time step. The diverse set of models included in this study give a good representation of the broad range of type of long-term energy models.

4.3.2 Industry sector model characteristics

The main differences in industry representation between the models assessed in this study can be found in the breakdown of industrial subsectors, explicit representation of material demand, drivers used to project final energy demand, explicit modelling of technologies and energy efficiency change, as descibed in Table 4-2[40].

Economic and demographic drivers are either directly related to industrial energy demand or to the demand for materials and industrial products, based on historical relations observed. By including material demand projections, various material production technologies and material recycling opportunities can explicitly be accounted for, which impact energy use per industrial product (Allwood, 2011; IPCC, 2014b). In CGE models, the projection of economic activity is the outcome of the production function, and energy intensity or material intensity improvements are typically represented by the substitution between capital, material, labor and energy inputs.

Some models include a diversifed set of current and future industry subsector specific technologies, characterized by their costs and efficiency. Technology deployment is modelled on the basis of relative costs, leading to more efficient technologies deployed when fuel prices increase. Other models do not account for technologies explicitly, but technology development is driven by either exogenous assumptions or for example learning-by-doing based functions.

Finally, an important difference in modelling are system boundary assumptions. Key differences among models are the inclusion or not of the energy use for feedstock purposes (also known as non-energy use of fuels) and the energy use in coke ovens and blast furnaces in the iron and steel industry. The energy use in refineries, agriculture and forestry are not included in the reported models industry data.

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[40] A more in depth description of the models in general and more specific details on their representation of the industrial sector can be found in Appendix 4A).

Table 4-2 Main industry model characteristics. Information acquired primarily from the FP7 EU ADVANCE industry models stock taking

IAM	Industry sector drivers	Industrial subsector breakdown	Technology	Efficiency improvements	Policy measures	Policy impact	Material trade (industrial goods)	Stock turnover	Recycling	Energy use as feedstock	Energy use in coke oven and blast furnaces [3]	Process emissions[4]
AIM-CGE	CES production function with the energy nested with value-added	Iron and steel[8], chemicals[8], non-metallic minerals[8], food processing, pulp and paper[8], construction, others (7)	No	CES nesting structure determines the technological energy efficiency and fuel use	Carbon tax or emission constraint with carbon tax	Price mechanisms	Yes	No	No	Only iron & steel	Only blast furnaces	From cement
DNE-21+	Material demand is related to production, consumption, import, export, population and GDP	Iron and steel[1], cement[1], pulp and paper[1], aluminium, some chemicals[1] (ethylene, propylene and ammonia) (7)	Yes	Exogenous per technology. More efficient technologies get a larger market share in response to higher fuel prices.	Carbon pricing, efficiency standards, and sectoral intensity targets.	Implementation rates of technologies and price mechanism	Yes (exogenous scenario)	Yes	Yes	Yes	In steel sector: Yes, other sectors: No	From cement, iron, etc.

IAM	Industry sector drivers	Industrial subsector breakdown	Technology	Efficiency improvements	Policy measures	Policy impact	Material trade (industrial goods)	Stock turnover	Recycling	Energy use as feedstock	Energy use in coke oven and blast furnaces [3]	Process emissions[4]
GCAM	Endogenously from land use model (for fertilizer), and total GDP (for the remaining industry)	Cement[1], nitrogenous fertilizers[1], others (3)	No, only for CCS	Technology improvement rates take into account the opportunities for improved energy efficiency, and are a scenario input assumption	Carbon taxes, emission constraints,	Modified fuel choices, production technologies and demands for industrial goods.	No	No	No	Yes	Yes	From cement
Imaclim-R	Endogenously from the equilibrium point between the supply and demand of industrial goods	None	No, only for CCS in cement and fertilizer	Autonomous, and fuel price induced energy efficiency	Carbon/energy taxes (or energy subsidies), emissions permits	Price mechanisms	Yes	Yes	Yes, but not explicitly	No	No	No
IMAGE	Material demand is related to economic activity and material intensity for steel and cement; energy intensity for other sectors	Steel[1], cement[1], other (3)	Steel, cement	Exogenous per technology more efficient technologies get a larger market share in response to higher fuel prices.	Carbon tax, prescribing certain efficient technologies	A dynamic response to changed technology costs (incl. fuel price) or prescribed technology mix	Yes, only for cement and steel	Yes	Yes	Yes	Yes	From cement

IAM	Industry sector drivers	Industrial subsector breakdown	Technology	Efficiency improvements	Policy measures	Policy impact	Material trade (industrial goods)	Stock turnover	Recycling	Energy use as feedstock	Energy use in coke oven and blast furnaces [3]	Process emissions[4]
MESSAGE	Total energy demand is related to GDP and population, based on historical energy intensity trends	Thermal and electric demand of total industry, non-energy use, cement process emissions	No, only CCS for process CO2 emissions explicitly represented	Improvement of energy intensity depends on long-term price development. Fuel switching implies efficiency changes. No explicit representation of energy efficiency technologies.	GHG and energy pricing, GHG emission cap, permits trading, fuel subsidies, capacity, production and share target regulations[4]	Price mechanisms and model constraints	No	No	No	Yes	In steel sector: yes, other sectors: no	From cement
POLES	Energy demand in industry depends on energy costs (short- and long-term effects) and an activity variable that is sub-sector dependent	Iron and steel[1], chemicals and petrochemicals[2], non-metallic minerals[2], others (4)	Boilers are described with a fixed cost, an efficiency and a lifetime	Improvement of energy intensity depends on long-term price elasticities. No explicit representation of energy efficiency technologies.	Taxation policy on energy fuels, which includes carbon pricing.	Price mechanism	Yes	(only for boilers)	No	Yes	Only own energy use in blast furnaces	From cement

IAM	Industry sector drivers	Industrial subsector breakdown	Technology	Efficiency improvements	Policy measures	Policy impact	Material trade (industrial goods)	Stock turnover	Recycling	Energy use as feedstock	Energy use in coke oven and blast furnaces [3]	Process emissions[4]
TIAM-UCL	GDP and other economic activity to derive energy demand or material demand	Pulp and paper[1], chemicals[2], iron and steel[1], non-metallic minerals[1], others (5)	Yes	Exogenous per technology more efficient technologies get a larger market share in response to higher fuel prices	Carbon tax/cap, permit trading, technology subsidy, efficiency requirements	Price mechanisms and model constraints	Yes, but not explicitly modelled	Yes	No recycling	Yes	Yes	No

[1] Modelling physical production and energy demand of the subsector; [2] Modelling energy demand of the subsector ;[3] transformation and own energy use; [4] The process emission that can be assigned to a specific sub sector.

4.4 Global Industrial model projections

4.4.1 Baseline scenario projections

Final Energy Demand

The baseline industrial final energy demand projected by each model (with and without feedstock use), are compared to the IEA WEO current policy scenario in Figure 4-2. In the short-term (next 20-30 years), all models project a steady increase of industrial final energy use, similar to the IEA projections. In the long-term, however there are clear differences in the projected trends, though these differences are not directly related to the different model assumption described in Section 3. MESSAGE and GCAM project a continuous high growth of energy demand, DNE21+ (running until 2050), AIM/CGE, TIAM-UCL, and IMAGE show moderate growth and saturation of energy demand at the end of the century while POLES and Imaclim-R show reduction of energy demand in the second half of the century. In 2100, this results in a range of more than a factor 2 between the highest and the lowest projection. The ratio of final energy demand in 2100 compared to 2010 (2010=1) is between 3.4 and 1.4, which is very comparable to final energy range of the much larger (120 BAU scenario) set of industry sector scenarios shown by the IPCC over the 21st century (IPCC, 2014a).

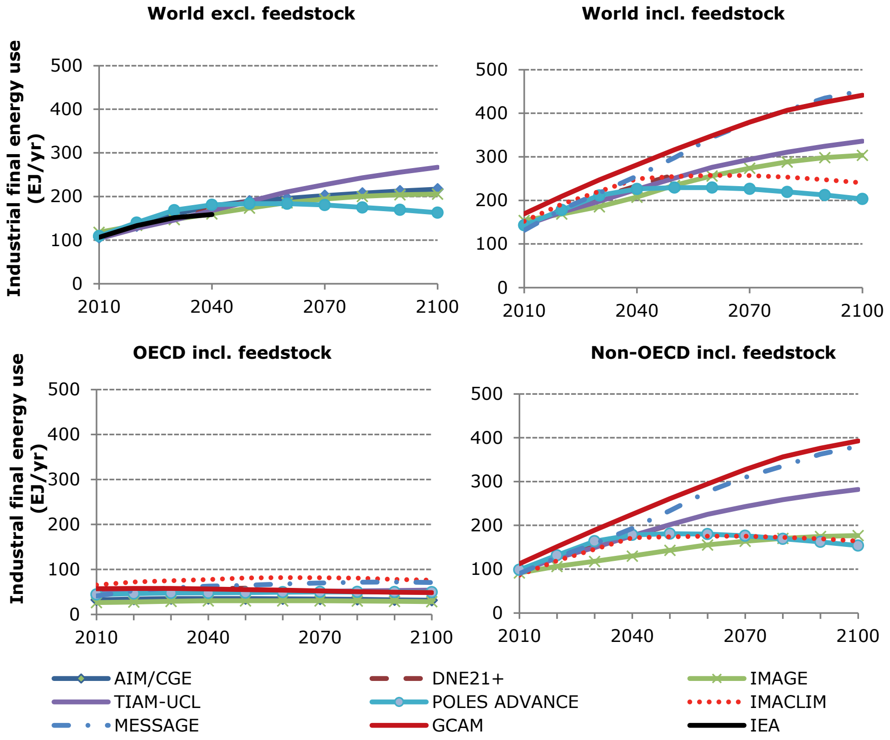

Figure 4-2 Baseline final energy demand projections in the industry sector up to 2100: a) Global excl. feedstock, b) Global incl. feedstock and c) OECD incl. feedstock and d) Non-OECD countries incl. feedstock.

Disaggregating the results between regions, shows that the final energy consumption pathways in Non-OECD countries is crucial in understanding these global trends (Figure 4-2d). All models project annual industrial final energy use in OECD countries to remain more or less constant compared to current values, while in Non-OECD countries industrial energy use is projected to grow significantly. How long this growth continues is a key uncertainty across models.

Energy intensity trends

Reduced energy intensity (E/$ GDP) can be the result of economic structural change (slower growth of industry sector activities than the overall economy), shifts towards higher-value goods produced by the industrial sector, and improved energy efficiency within an industrial sub-sector. Between 1995 to 2010, the reduction in energy intensity (w.r.t. industrial value added (IVA)) has been higher in OECD countries than in Non-OECD countries, but starting from a much higher level (17 MJ/$IVA in Non-OECD 1995 as opposed to 9.5 MJ/$IVA in OECD) (IEA, 2015). Literature suggests that a key factor in the energy intensity decline in developing countries has been technological change while in developed countries shift towards high tech industry has had a larger impact on energy intensity reduction (Olivier, 2013; UNIDO, 2011). Moreover, the share of IVA in GDP has decreased in OECD countries which decreased the energy intensity compared to GDP even further, as can be seen in Figure 4-3.

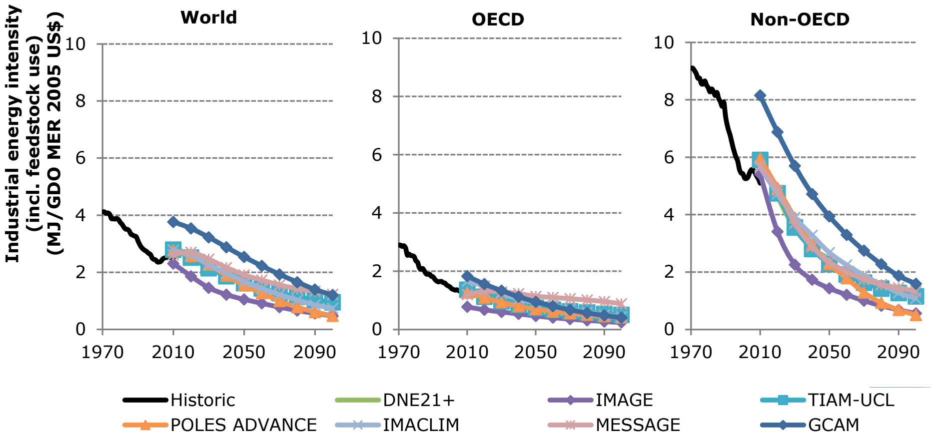

Figure 4-3 Industrial energy intensity expressed in final energy use/GDP MER (in USD $2005) for different regions: a) global, b) Non-OECD countries and c) OECD countries. From 1970-2005 historic energy intensity values (IEA, 2015) are shown in black.

The historical energy intensity trends are compared to the modelled energy intensity futures. The models project energy intensity of Non-OECD countries in the coming century to decline with annual reduction rates ranging from 1.8-2.2%. This relative reduction significantly larger than the average 0.6% measured empirically between 1970 and 2010. In OECD countries energy intensity continues, but with lower annual reduction rates varying between 0.3 and

1.65%, compared to the historic average of 2.7%. As mentioned, this historical reduction in OECD countries is largely the result of reducing IVA share in GDP. A key uncertainty for future industrial final demand is whether energy intensity in non-OECD countries converges to projected OECD levels.

Energy consumption by fuel type

In Figure 4-4 the projected industrial final energy per fuel type is shown for the year 2010, 2030, 2050 and 2100. AIM/CGE and IEA results do not include industrial feedstock use. Interestingly, there is a reasonably large agreement across the modelled fuel shares, remaining close to current shares. Fossil fuels are projected by all models to take up more than 50% of the industrial fuel use in 2100. Most models, except Imaclim-R and TIAM-UCL project a slight increase in electricity use and a decrease in fossil fuel use, both between 10-20% change. The electricity and gas shares in the models are relatively low compared to IEA scenarios, projecting respectively 31 and 21% in 2030.

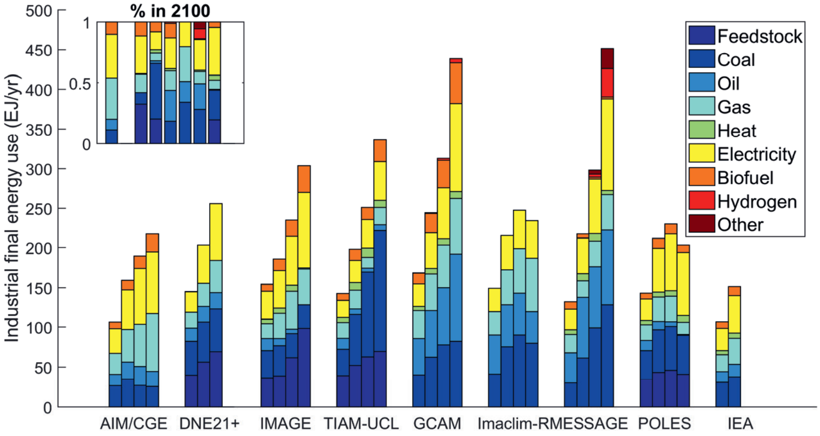

Figure 4-4 Baseline final energy demand of the industry per energy carrier in 2010, 2030, 2050 and 2100. The reported values include feedstock use for MESSAGE, GCAM and IMACLIM, which in 2010 is mainly oil use in the chemicals and petrochemicals sectors, and cokes in the iron and steel sector. In the top left the fuel shares in 2100 are shown.

4.4.2 Mitigation scenario projections

In the stringent climate policy scenario all models show a decrease in final energy demand compared to the baseline (Figure 4-5 left panel). The range of industrial final energy use in 2100 drops from 195-451 EJ to 115-306 EJ, i.e. which is compared to baseline a reduction of 10%-50%. The IEA project a reduction of 18% in 2035. TIAM-UCL, GCAM and MESSAGE project a more or less constant reduction in time, while IMAGE, POLES, AIM-CGE and Imaclim-R show a high reduction in the first 50 years and continue with a steady percentage.

Interestingly, the models with low industrial energy demand (with the exception of TIAM-UCL) in the baseline find that there is potential to decrease the industrial energy intensity even further to reach a climate target, and this decrease occurs in those models more rapidly in the coming decades than in the other models.

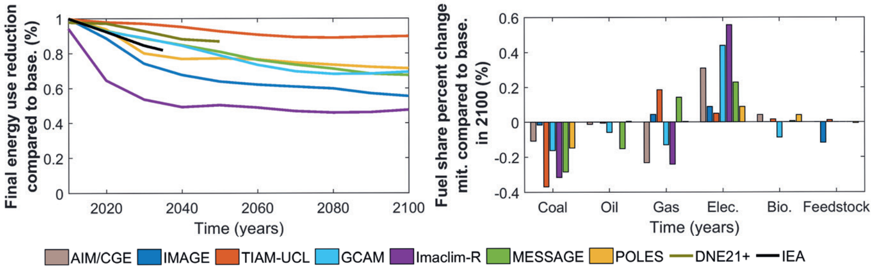

Figure 4-5 a) Mitigation scenario final energy demand as a portion of the baseline scenario final energy demand and b) Percent change in fuel share mitigation scenario compared to baseline.

The fuel mix changes significantly in the mitigation scenario which can be seen in Figure 4-5b, showing the percentage change in fuels shares in 2100 between a mitigation scenario to a baseline scenario (indicating how flexible the model is to switch to different fuels as a response to higher fossil fuel prices). All models except IMAGE show a significantly lower use of fossil fuels in the mitigation scenario. The general trend is a decrease in coal use and an increase in the use of electricity to reduce industrial emissions. This transition takes place steadily over time. TIAM-UCL and MESSAGE also show a switch from coal to gas.

Oil and biomass shares do not change severely in all models. Although IEA scenarios show a significant contribution of biomass to CO_2 emission reduction (IEA, 2010, 2012b), in this set of long term energy models deploying biofuels as a mitigation measure is less attractive than switching to electricity to decrease emissions. The apparent shift towards electricity is significantly larger for AIM/CGE, GCAM, Imaclim-R and MESSAGE than other models. It should be noted though that these models do not model industrial manufacturing processes explicitly, which could explain a higher flexibility in fuel switching. In technology-rich models the additional information on preferred fuels for different processes and/or the lack of more advanced technologies in the model's representation could constrain fuel switching.

This divergent behavior highlights a broader issue that is relevant for modeling future industrial energy use: that is, the appropriate level of detail at which to model the products manufactured, and the specific of the manufacturing technologies used. In this exercise, the more aggregate models tend to represent many industrial subsectors together with generic production technologies in which all fuels are substitutes, which may be unrealistic for many industrial processes. However, process-based, technologically detailed models may not have the capacity for future fuel-switching, simply because the technologies that would enable future fuel-switching do not currently exist. In the past few decades however, electric arc furnaces in the steel industry and mechanical separation technologies in the chemicals industry have led to increasing shares of electricity in both of these industries.

The different approaches to reduce these industrial emissions are summarized in Table 4-3. Variation across models lie in the extent and rapidness of energy intensity reduction, and flexibility to switch fuels as discussed in the previous paragraphs. In models where both approaches have a limited application (e.g. TIAM-UCL, MESSAGE), other sector's emission budget will be more constrained.

Table 4-3 Annual reduction with respect to 2010 of energy intensity, CO_2 intensity and CO_2 emissions in the models mitigation scenario. The relative high value are marked bold.

	Energy intensity (MJ/$)		CO2 intensity (g/MJ)		CO2 emissions	
	2050	*2100*	*2050*	*2100*	*2050*	*2100*
DNE21+	1,45		1,23		0,12	
IMAGE	2,95	2,25	1,60	1,55	1,66	1,45
TIAM-UCL	1,53	1,30	0,85	0,91	-0,38	0,08
POLES	2,09	2,31	1,54	1,78	1,01	1,77
Imaclim-R	2,79	2,20	1,93	1,78	2,21	2,03
MESSAGE	1,30	1,26	1,93	1,78	0,43	0,86
GCAM	1,56	1,66	1,84	6,91	0,89	6,29

4.5 The cement industry – subsector model comparison

To get a better impression of how the industrial sub-sectors are represented in the models, in this section we take a closer look into the projected material production and energy use for the cement industry of the IMAGE, DNE21+, AIM/CGE, POLES, GCAM and TIAM-UCL models for the baseline scenario (only for these models data was available). For comparison, also the IEA projection for the 6ºC scenario (6DS) is shown (IEA, 2012b).

The reason to focus on the cement industry is that it represents a considerable share of global industrial energy consumption and GHG emissions. In 2009, the global cement industry consumed 11 EJ, which is 11% of global industrial energy consumption (excl. feedstock use) and emitted 2.3 $GtCO_2$ which is 26% of global industrial GHG emissions of which more than half were process emissions from calcination (IEA, 2011). Several studies have identified technologies/measures that can limit the energy use and GHGs, and improve material efficiency in this sector (JRC/IPTS, 2010; WBCSD/CSI-ECRA, 2009; Worrell, 2013). Another reason to focus on this sector is that compared to the other major energy intensive industries, the cement industry is less complex. Cement is almost entirely used by the construction industry. Cement plants globally use the same three process steps i) raw material preparation, ii) clinker calcination, and iii) final material preparation. In addition, trade between the different countries is limited as cement transportation is very costly. In 2009, only 4.5% of cement consumption was traded (Harder, 2008), meaning that for most countries, and certainly the large regions covered in models, cement production is equal to cement consumption.

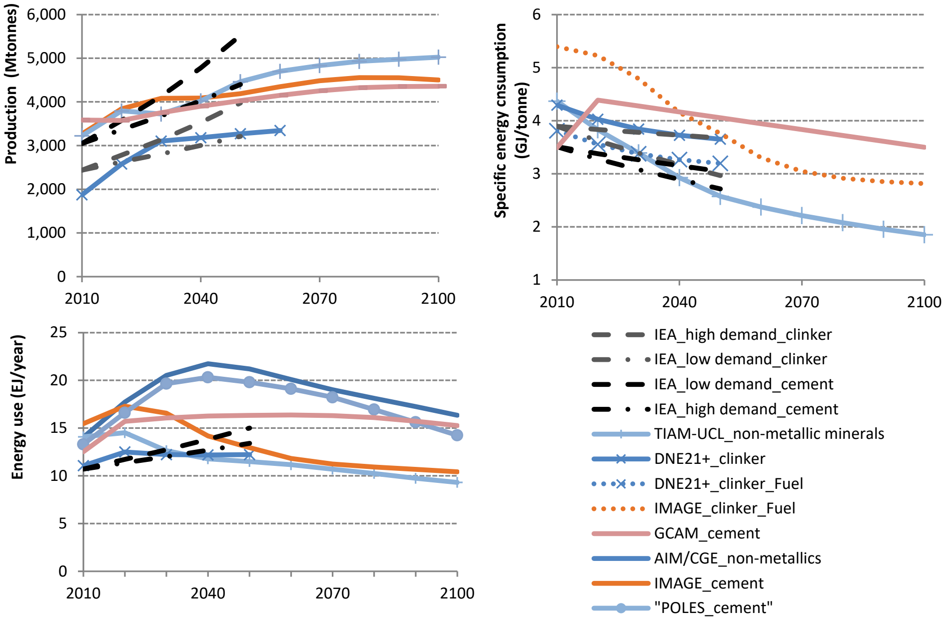

Figure 4-6 a) Projected material production in the non-metallics/cement industry b) energy use c) specific energy consumption for cement and clinker making in different long-term energy models under the baseline scenario in different long-term energy models in comparison with the IEA projections

Figure 4-6a shows the projected production of cement in GCAM and IMAGE, the production of non-metallic minerals in TIAM-UCL and the production of clinker in DNE21+, that model material use explicitly. The global cement production in 2010 was 3.2 Gtonnes (USGS, 2013) and the global estimated clinker production was 2.4 Gtonnes (based on a clinker to cement ratio of 76%)[41] (WBCSD/CSI, 2012). In IEA, clinker production increases from 2.4 Gtonnes in 2009 to 3.2 and 4.0 Gtonnes in 2050 under the low demand and the high demand scenarios, respectively. Compared to the IEA projections, the three models forecasts are on the low side of the projections (IMAGE is calibrated to 2005). This is due to lower growth rates and different calibration years. In addition, all long-term energy models show a saturation of demand, while the IEA projects steady growth.

The projected energy demand for the non-metallics/cement industry by IMAGE, GCAM, TIAM-UCL and DNE21+ peaks relatively early and then levels off or even declines (Figure 4-6b). AIM/CGE and POLES project the energy demand to peak at a much later year (2040) after which also a decline is observed. The IEA projections show continues growth rates, in line with the earlier observation on material production rates. The models show again show

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[41] Although there is data available on cement production, data on clinker production is not. Therefore, clinker production is usually estimated based on information concerning the clinker to cement ratios. The clinker to cement ratio reported by the WBCSD/CSI (2012) is lower from the clinker/cement ratio of 80% reported in IEA (2012b). For an 80% clinker/cement ratio, the 2010 clinker production would be 2.56 Gtonnes.

difference in base year data. All models project that the cement sector share in total industrial final energy use decreases.

Figure 4-6c shows the development of specific energy consumption (GJ/tonne product) for cement and clinker making in the various energy models. This is projected to decline in all models driven by technology development (with exception of the GCAM results for the first 20 years of the projection). In IEA, the 2009 energy use for cement making, 3.5 GJ/tonne cement, is forecasted to drop to 3.1 and 2.7 GJ/tonne by 2050 under the low and high demand scenarios, respectively. In clinker making, the energy use (mainly fuel) is projected to decline from 3.9 GJ/tonne clinker in 2009 to 3.7 and 3.0 GJ/tonne clinker in 2050 in the low and high demand scenarios, respectively (IEA, 2012b). That is an annual decrease in the specific energy consumption of clinker calcination of 0.14 or 0.66%.

The annual decline rates of the specific energy consumption during the 2010-2050 period, for clinker/cement/non-metallics production are about 0.40%, 0.42% and 1.31% for DNE21+, IMAGE and TIAM-UCL respectively, compared to the IEA range of 0.56-0.85% for cement making. Literature suggests that the energy use for clinker making can drop to 2.9 GJ/tonne clinker (JRC/IPTS, 2010) and when improved equipment for cement making and lower clinker to cement ratios are used the energy use could drop to 2.1-2.7 GJ/tonne cement (IEA, 2012b; Kermeli et al., 2014). This means that considerable improvement of the energy intensity would still be possible in the mitigation scenarios.[42]

The detailed focus on the cement sector here shows that understanding how total industrial projections relate to subsector material, energy demand and technology deployment improves the ability to interpret the scenario results.

4.6 Discussion and conclusion

4.6.1 Discussion

Comparing the industrial sector representation in long-term energy models has revealed some striking similarities in the projected energy use pathways. Energy intensity (w.r.t GDP) in Non-OECD regions is projected to decrease more rapidly over the coming century than the one observed in recent decades with annual reduction rates varying between 1.8-2.2%, compared to average annual reduction of 0.6% between 1970 and 2010, which is a clear trend break. OECD countries final energy use remains close to current energy use ranging between 36 and 71 EJ/yr in 2100 across the models. Similarly, industrial fuel shares remain close to current values, with electricity use increasing slightly and fossil fuel use decreasing, both between 10-20% change.

Still, projected industrial carbon emission pathways cover a broad range across the models (between 7.5 and 24 Gt/yr in 2100). This can be explained by already different base year assumptions in fuel shares, energy consumption and accompanying emissions, as well as diverging trends of final energy consumption in Non-OECD countries in the second half of the century. These differences could be significantly larger if for example Non-OECD countries

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[42] The IMAGE energy intensity values are relatively high as they are the energy use for cement making divided by the tonnes of clinker production.

would not decouple so strongly from GDP as seen in current projections, or if there is a higher shift to electricity.

To assist the result comparison, describing in detail how the industrial module works and thereby increasing transparency in each model is of great importance. The base year final energy data differs per model and in order to make a credible comparison, reporting the industry boundaries is important. Feedstock use accounts for 17% of industrial energy consumption and it should be clear whether it is accounted for. The same holds for the energy use in coke ovens and blast furnaces and in refineries. In the cement/nonmetallic comparison the same effect is visible but by specifying which production processes are accounted for, the variation can be clarified.

The industry data comparison has shown that the models project different appropriate measures to mitigate emissions. Some models show that to mitigate GHG emissions a significant reduction of final energy demand needs to take place in the coming decades, while other models remain close to their baseline final energy levels and rely more on fuel shifting. Comparing long-term energy models at the sub-sector level, such as done in this analysis for the cement sector, can improve our understanding of differences and similarities underlying the model projections. Moreover, comparing bottom-up model details to sector-specific case studies could improve projections, and increase the ability to assess sector specific mitigation policies– at least in the short term. For example, comparing the projected SEC of cement production to state-of-the-art knowledge shows that energy intensity for cement making could reduce further than currently assumed in the models.

Using energy intensities of specific countries/regions, in combination with projected material demand to model industrial future energy, could help to understand the role of recycling, material efficiency, and technology efficiency in mitigating emissions. This can help to clarify what levels of energy intensity improvements are reasonable to achieve, which share of the energy use can be replaced by less carbon intensive fuels, and how fast both processes could take place. For example, by improving the material efficiency in cement making, by using higher amounts of supplementary cementitious materials at different stages of cement production. On the long term constraining industrial technology change to what is currently known on the other hand might be detrimental, as unknown technology options are not accounted for.

Accounting for material demand at sub-sectorial level has as additional advantage that, in the integrated structure that global system models operate, it provides the opportunity to relate the material demand to activities that require material, which are also represented in the model. An example would be to relate cement demand to construct future infrastructure and building requirements, which could give more guidance in better projections of material demand saturation.

4.6.2 Main conclusions

In the reference baseline scenario, the projected behavior across the models is comparable in the coming decades: the industry sector is relatively energy intensive and remains reliant on fossil fuel (>50%)– but in the second half of the century energy use models project either continuous growth or saturation. This leads to more than a factor of 2 difference between the highest and the lowest industrial energy demand projection in 2100, ranging between 203 and 451 EJ/yr. Saturation of industrial energy demand depends strongly on whether Non-OECD countries are projected to reach similar energy intensity levels as achieved in OECD countries, which is a key uncertainty across models.

Models show different responses to mitigate CO_2 emissions, where uncertainties are the potential of fuel switching or energy intensity improvements. The reduction of final energy use in 2100 compared to the baseline scenario span a range of 10%-50%. The models show a switch from coal to electricity use as a measure to reduce industrial emissions. Explicitly modelling industrial technologies can constrain the flexibility to use different fuel types and this is recognized in the mitigation scenario results, as models with rich technology representation tend to project less variability in to switch fuels as a measure to mitigate GHG emissions. This divergence highlights that understanding of economy-wide mitigation responses and costs is an area for future improvement in the models.

In line with Sathaye et al. (2011) using industry subsector material and energy use details to support the projected mitigation potential can provide insight in feasibility of how emissions reduction can be achieved. More information at a subsector level could improve the understanding of what realistic energy intensity improvements as a result of material usage and technology efficiency changes are in the short term, along with the potential to use less carbon intensive fuels. Moreover, this would create the opportunity to relate material demand to non-economic drivers, such as infrastructure growth and building stock turnover to improve the understanding of demand saturation and assess the role of subsector specific climate policies to mitigate emissions.

Acknowledgement
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Appendix 4A Overview of participating models

Asia-Pacific Integrated Model – Computable General Equilibrium (AIM/CGE).

The AIM/CGE model, developed by the National Institute for Environmental Studies in Japan, has been widely used for the assessment of climate mitigation and impact (Fujimori et al., 2014b; Hasegawa et al., 2014; Hasegawa et al., 2015). The AIM/CGE model is a one-year step recursive-type dynamic general equilibrium model that covers all regions of the world. AIM/CGE has an option to be used as country mode (Thepkhun et al., 2013).

The industrial sectors are assumed to maximize profits subject to each input price. The production function is multi-nested Constant Elasticity Substitution (CES) functions. The production structure starts from fixed coefficient (Leontief) with two inputs; namely energy-value added and intermediate inputs. The energy-value added bundle is further nested by CES which has a price elasticity of 0.4. The energy inputs are again nested by CES of each energy carrier and the elasticity is 1.0. The value added is aggregated by labor and capital inputs where elasticity is 1.0. The capital is distinguished by newly installed and already existing one

Instead of using typical CES function, there is an option to couple very detailed technological information for energy end-use sectors (more than 300 kinds of technologies) adopted in AIM/Enduse which is bottom-up type model (Fujimori et al., 2014c). To assess bioenergy and land use competition appropriately, agricultural sectors and land use categories are also highly disaggregated (Fujimori et al., 2014a).

Dynamic New Earth 21 plus (DNE-21+).

DNE21+ is an energy-related CO_2 emission assessment model developed by the Research Institute of Innovative Technology for the Earth (RITE) in Japan. The model is the key assessment model of RITE’s integrated assessment framework, and an optimization type of bottom-up linear programming model, highly technologically detailed, where the global costs are minimized when policies such as carbon tax, emission cap, and energy standard are applied (Akimoto et al., 2010; Akimoto et al., 2008). The salient features of the model include (1) analysis of regional differences with fine regional segregation (The world is divided into 54 regions.), (2) a detailed evaluation of global warming measures by modelling around 300 specific technologies that can be used to counter global warming, and (3) explicit considerations on facility transition for the specific technologies over the entire time period. Historical capital stocks by energy efficiency levels of the specific technologies are assumed considering regional current differences in energy efficiency (Oda et al., 2012).

n DNE21+, the industrial sector is broken down into the iron and steel, cement, pulp and paper, aluminium, some chemicals (ethylene, propylene, and ammonia) and the others sub-sectors. All sub-sectors are modelled following a bottom-up approach except for the others subsector which is modelled in a top-down way (Oda et al., 2007). The future material demand is estimated based on historical relationships between production, consumption, imports, exports and GDP and population levels. Furthermore, availability of steel scrap is also considered for developing future crude steel scenario (Oda et al., 2013).

Global Change Assessment Model (GCAM).

GCAM, previously known as MiniCAM, is an integrated assessment model developed by the Joint Global Change Research Institute (JGCRI 2014), at the Pacific Northwest National Laboratory. It links the world's economy, energy, agriculture, land use and technology systems together with a climate model to assess a variety of climate change policies (U.S. EPA 2013; GCAM, 2015). It has been used in a number of climate change assessment and modelling activities such as the Energy Modeling Forum (EMF), the U.S. Climate Change Technology Program, and the U.S. Climate Change Science Program and IPCC assessment reports. GCAM is freely available as a community model (JGCRI, 2014).

In GCAM, the energy demand in the industrial sector is derived from a constant elasticity equation where energy demand is indexed to GDP change (Brenkert et al., 2003). The demand for cement is driven by GDP and the demand for fertilizers is determined by the land use module. For the remaining industrial sectors, GCAM models a single homogeneous industrial good.

Imaclim-R.

The Imaclim-R model (Waisman et al., 2012) is a multi-region and multi-sector model of the world economy. It combines a Computable General Equilibrium (CGE) framework with bottom-up sectoral modules in a hybrid and recursive dynamic architecture. It is developed by the Centre International de Recherche sur l'Environnement et le Développement (CIRED). Imaclim-R studies the relationships between energy systems and the economy and can be used to assess the feasibility of climate change strategies and the transition options towards a global low-carbon future (ADVANCE, 2015). In Imaclim-R, industrial energy use is not modelled with disaggregated technologies. The energy intensity of the industry sector decreases over time due to price-induced energy efficiency improvements and due to new installed capacities characterized by higher efficiencies. In the industrial sector, structural change (a decrease in the activity of the heavy industries as compared to the manufacturing industries) leads to an additional decrease in energy intensity. To represent saturation of industrial goods consumption, the income elasticities of consumption of industrial and agricultural goods are assumed to decline with increasing per-capita income (Waisman et al., 2012).

Integrated Model to Assess the Global Environment (IMAGE).

The Integrated Model to Assess the Greenhouse Effect (IMAGE), was developed by PBL Netherlands Environment Assessment Agency. The IMAGE model is an IAM that simulates the environmental consequences of human activities in industry, housing, transportation, agriculture and forestry worldwide. It represents large scale and long-term interactions between human development and natural systems to gain insight into the processes of global environmental change, assesses options for mitigation and adaptation, and identifying levels of uncertainty. A great number of global studies, such as the IPCC Special Report on Emissions Scenarios (SRES), the UNEP Third Global Environment Outlook (GEO-3) and the Millennium Ecosystem Assessment (MA) have used the simulated results from IMAGE (Stehfest et al., 2014; Bouwman et al., 2006).

In the industrial module of IMAGE, the final energy demand is modelled as a function of changes in population, economic activity and energy efficiency. The change in energy-intensity (i.e. energy units per monetary unit) is assumed to be a bell-shaped function of the level of per capita activity (i.e. sectoral value added or GDP). The industrial energy intensity can decrease due to autonomous energy efficiency improvements but also due to increased energy prices. To model the decrease in industrial energy intensity two multipliers are used; 1) an Autonomous Energy Efficiency Increase (AEEI) multiplier which is linked to the economic growth rate, representing energy efficiency improvements that occur as a result of technology improvement independent of energy prices, and 2) The Price-Induced Energy Efficiency Improvement (PIEEI) multiplier which is used to describe the effect of (rising) energy costs on energy intensity. The PIEEI multiplier is calculated with the use of a sectoral energy conservation supply cost curve and end-use energy costs.

The material demand (in tonnes of product) and production technologies for two industrial sub-sectors; the iron and steel and the cement industrial sub-sectors are explicitly modelled. The material demand is a function of the economic activity and material intensity. Once the consumption level has been determined, a material production model simulates how to fulfil the demand for steel and cement, taking into account trade, stock turnover, recycling, and competition between different steel and cement production technologies The material production is met by different steel and cement producing technologies, which are characterized by investment cost, fuel costs and energy requirements. For all the remaining industrial sub-sectors, the energy demand is modelled based on activity data, structural change, and the AEEI and PIEEI, as described above.

Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE).

The MESSAGE IAM, is a technology detailed hybrid model (energy engineering partial equilibrium model linked to general equilibrium model), developed by the International Institute for Supplied Systems Analysis (IIASA) for energy scenario construction and energy policy analysis (ADVANCE, 2015). Its results have been used in major international assessments such as the Intergovernmental Panel of Climate Change (IPCC) and the Global Energy Assessment (GEA) (IIASA 2012).

The industrial sector in MESSAGE is not disaggregated into the various industrial sub-sectors. The total industrial energy demand is generated using regression analysis with the use of historical GDP/capita and final energy use data as well as GDP and population projection data (ADVANCE, 2015).

Prospective Outlook on Long-term Energy Systems (POLES).

The POLES model is an econometric, technology detailed, partial-equilibrium model initially developed by the Institute of Energy and Policy and Economics (IEPE, now known as LEPII-EPE), Enerdata and the Institute for Prospective Technological Studies (IPTS) (JRC/IPTS, 2010). POLES is primarily used for energy demand and supply projections, analysing greenhouse gas emission reduction pathways, and assessing the impacts of technological change. It has been used for policy evaluation purposes by the EU-DG research, DG Environment, DG TREN, the French Ministry of Ecology and the Ministry of Industry (Criqui, 2009).

The industrial sector is disaggregated into the iron and steel, non-metallic minerals (cement and glass), chemical (including feedstock use) and the rest of the industry sub-sectors (including non-energy use) (Criqui, 2009; JRC/IPTS, 2010) and it entails detailed technological modules for the sub-sectors iron and steel, aluminium and cement (Russ et al. 2007). The industrial final energy demand depends on energy costs, either income or sub sector specific national value added, and autonomous technological trends (Criqui, 2009; JRC/IPTS, 2010). Improvements in energy intensity depend as well on long-term price elasticities.

TIMES Integrated Assessment Model – University College London (TIAM-UCL).

TIAM was developed by the Energy Technology Systems Analysis Programme (ETSAP). The ETSAP-TIAM model has been used for the analysis of different climate change mitigation policies (Anandarajah et al., 2011). The TIAM-UCL energy systems model is a global optimization model that investigates decarbonisation of the global energy-environment-economy system.

Industrial energy services modelled in TIAM-UCL are chemicals, iron and steel, non-ferrous metals, non-metals, pulp and paper and other industries. The material demand is modelled for iron and steel, pulp and paper and non-metals, while in the remaining industrial sub-sectors the total energy demand is related directly to economic activity. The development of industrial sectoral growth rates are geared to GDP. A shift in the GDP composition towards the service sector is implied, so that agriculture and industry will become less important for the whole economy in the future. Demand drivers (population, GDP, etc.) are obtained externally, via other models or from other sources (Anandarajah et al., 2011)

TIAM-UCL models a large number of technologies in the industrial sector to meet the energy-service demands (divided into steam, process heat, machine drive, electro-chemical processes and other). To satisfy every energy-service of each industry, the existing technologies, characterized by an efficiency, an annual utilization factor, a lifetime, operation costs, and six seasonal share coefficients are represented in the model for the base year. New technologies progressively replace the existing ones. Regional specific hurdle rates are applied to new technologies varying from 10% for developed countries to 20% for developing countries.

5 The scope for better industry representation in long-term energy models: modeling the cement industry[43]

Abstract

Although the cement industry emits around 6% of global CO_2 emissions, most global Integrated Assessment Models (IAMs) barely represent this industrial subsector or do not cover all important processes. This study, describes the state-of-the-art of cement modelling in IAMs, suggests possible improvements and discusses the impacts of these on energy and greenhouse gas emissions (GHG) in the IMAGE global IAM.

It is found that two cement-sector specific GHG mitigation measures are often not explicitly accounted for in IAMs, namely: i) retrofitting and ii) reducing the clinker to cement ratio. For retrofitting, many measures are identified as cost-effective and when incorporating these in the IMAGE model overall energy use reduces between 2010-2035 by 9.8 and 11 EJ (4% and 5%) under the baseline and GHG mitigation scenarios, respectively. When incorporating the clinker to cement ratio by linking material availability to the activities in the steel industry and coal-fired power plants, the 2050 energy use reduces by 15% under the baseline scenario and increases by 9% under the GHG mitigation scenario as fewer coal-fired power plants are in operation. This is even more prominent in the long term. The 2100 energy use is 14% higher in the GHG mitigation scenario as even fewer coal-fired power plants are in operation drastically limiting the potential for clinker substitution with fly ash. These results highlight the importance of capturing cross-sectoral relationships between industries and of including sector specific mitigation measures in long-term energy models.

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[43] Based on: Kermeli, K., O.Y. Edelenbosch, W. Crijns-Graus, B.J. van Ruijven, S. Mima, D.P. van Vuuren, and E. Worrell. (2019). The scope for better industry representation in long-term energy models: modeling the cement industry. *Applied Energy* 240, 964-985.

5.1 Introduction

In 2014, the global industrial sector consumed 154 EJ[44] and emitted 8.3 $GtCO_2$[45], being responsible for 36% of global energy consumption and about 24% of direct CO_2 emissions (IEA, 2017). The International Energy Agency (IEA) (2014c) projects that without any further actions taken, by 2040, industrial energy use will reach 171 EJ and CO_2 emissions will amount to 15 $GtCO_2$ (still around a third of energy use and emissions).

Energy models, such as those included in Integrated Assessment Models (IAMs), are used to project global energy use and greenhouse gas emissions (GHGs) and to analyze the potentials and the associated costs of several energy and GHG mitigation options. Major international assessments such as the Intergovernmental Panel of Climate Change (IPCC) special reports, and the Global Energy Assessment (GEA), for instance, rely heavily on the scenarios produced by IAMs (IPCC, 2014; IAMC, 2014; GEA, 2012). Due to their global and economy-wide scope, the level of detail in the industry modules of many IAMs is often not detailed enough to allow for sector specific technology representation (Sathaye et al., 2010; Rosen and Guenther, 2015), with many of the IAMs assessing the industry in an aggregated manner without sub-sector division (Edelenbosch et al. 2017). Still, making good estimates of the short and long-term energy and GHG reduction potentials and associated costs, and understanding the material demand and resource availability and their impact on energy use is very important when evaluating mitigation strategies and developing industry specific policies.

In an effort to understand and potentially improve the way the industrial sector is modelled in IAMs, we focus this analysis on the cement industry. In 2014, the cement industry consumed 10.6 EJ of energy (7% of industrial energy use). Due to the high level of process emissions, cement production comprises the second largest industrial emitter, following the iron and steel industry, accounting for 27% (2.2 $GtCO_2$ in 2014) of industrial emissions and 6%[46] of global CO_2 emissions (IEA, 2017). In addition to being a major industrial energy consumer and GHG emitter, it comprises an industry with limited complexity and can therefore easier be incorporated in existing IAMs than other industrial sub-sectors. Its limited complexity is due to a number of factors. Most cement is consumed in a single sector: the construction sector. Therefore, cement consumption could be linked to construction activity. In addition, trade is limited as cement is mainly consumed in the country of production. Moreover, the cement manufacturing process is common to all cement plants (although the raw materials or additives vary between countries). Another reason for focusing on this industry is that it is an industrial sub-sector already explicitly modeled in a number of IAMs. Yet, there are many IAMs that model it as part of the non-metallics minerals sector or do not model it at all (Edelenbosch et al., 2017).

Increasing the level of detail can raise practical issues such as the need for larger computational requirements and expertise needs for operating the model. Except for these practical issues,

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[44] Including energy use in blast furnaces and coke ovens in the steel industry, energy use as feedstock (25 EJ in the chemical and petrochemical industry) and industry own use.

[45] Does not include indirect CO_2 emissions for electricity generation.

[46] In 2014, global CO_2 emissions from fuel combustion amounted to 32.2 $GtCO_2$ and industrial process CO_2 emissions to 2.0 $GtCO_2$. The cement industry was responsible for 70% of total process emissions (IEA, 2017).

higher detail in models made for long-term global projections could constrain the model too much with detailed knowledge on current technologies (Krey, 2014). Still, over the last few years, some models have started to add more technology detail on end-use sectors, including the industry sub-sectors, for the advantages described above. Few long-term energy models have a module with bottom-up details that specifically targets the cement industry. IMAGE, a global integrated assessment model, has an embedded module dedicated to the cement industry used to analyze future projections on energy use and GHG emissions (van Ruijven et al., 2016). It covers global and regional clinker and cement demand and production that take into account trade of both materials, choice of production technologies, stock turnover and energy use and GHG emissions. Another example is POLES, which has the option to project regional energy use and CO_2 emissions while taking into account production technologies, stock turnover and retrofitting (IPTS, 2003).

In this paper, we investigate the scope for adding further bottom-up details to long-term IAMs. We do this by adding more detailed information to a single example model, i.e. the IMAGE model. In the Discussion section, we look into the question whether similar improvements can also be made to other models. For the less detailed models, that do not model the cement industry, or they model it in a more aggregated manner, a set of guidelines for modeling the cement industry was developed. The guidelines can be found in Appendix 5B.

This paper is structured as follows. In Section 5.2 we discuss the current representation of the cement industry in long-term models. In Section 5.3, we provide information from bottom-up analysis that could be used to improve the representation in IAMs. In Sections 5.4 and 5.5, we implement these improvements in IMAGE and present their impact on both global and regional model results covering in this way both industrialized and developing countries and emerging economies. Finally, in Section 5.6, we discuss our results and draw the main conclusions.

5.2 Representation of the cement industry in long-term energy models

Different models are used for long-term energy sector explorations. In the literature, models are referred to as Integrated Assessment Models (IAMs) if they include a wider representation of the economy and earth systems details and to energy system models if they don’t. Here, however, we refer to all of them as long-term energy models. Based on the information collected in the EU-FP7 ADVANCE project[47] (see also Edelenbosch et al., 2017). Table 5-1 provides a brief overview of the representation of cement industry in these models.

Most models treat the non-metallics minerals sector as a whole (Table 5-1). Out of the eight long-term energy models, only DNE 21+ and IMAGE explicitly model the cement industry, while Imaclim-R and MESSAGE do not have a representation of the cement industry or the non-metallic minerals sector. POLES models the non-metallic minerals sector but also has a technologically detailed cement module that can be activated on demand. Although the cement industry accounts for most of the energy use in the non-metallics sector, about 70-80% based on IEA (2007), the non-metallics sector includes the production of a variety of materials such

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[47] European Union Seventh Framework Programme FP7/2007-2013 ADVANCE project: http://www.fp7-advance.eu/

as copper, glass, lime, bricks and tiles which are produced with different processes; industrial sub-sectors that in general have different characteristics.

Table 5-1 Main characteristics of models participating in survey (Edelenbosch et al., 2017)

Model	Model type	Disaggregation of the industrial sector	Separate modeling of the cement industry
AIM-CGE	CGE	Yes	No (non-metallic minerals)
DNE 21+	Energy system model	Yes	Yes
GCAM	Hybrid/IAM	Yes	No (non-metallic minerals)
IMAGE	Hybrid/IAM	Yes	Yes
POLES	Energy system model	Yes	No (non-metallic minerals)[2]
TIAM-UCL	IAM based on bottom-up energy model	Yes	No (non-metallic minerals)
Imaclim-R	Hybrid CGE with sectoral bottom-up modules	No[1]	No
MESSAGE	IAM based on bottom-up energy model	No	No[3]

[1] Industries are divided into energy-intensive and non-energy intensive.

[2] There is detailed cement module also available (see for details JRC/IPTS, 2013).

[3] Only process CO_2 emissions from clinker burning are modeled.

As shown in Edelenbosch et al. (2017), baseline scenario projections of global material production (clinker, cement, or non-metallic minerals), energy use and energy intensity (GJ/tonne) differ quite significantly among long-term energy models. Constructing a baseline scenario that can well represent the industrial sub-sector by taking into account specific industry characteristics is key in making reliable GHG abatement estimates.

While several large-scale global models represent industry sectors energy use on the basis of their economic activity, here we concentrate on those that also represent physical demand of cement (e.g. in tonnes) and therefore can be directly coupled to bottom-up information. Most models that simulate the physical demand are based on historically observed correlations between economic activity and material intensity (e.g. Akashi et al., 2011; Anand et al., 2006; Groenenberg et al., 2005; Pardo et al., 2011). In general, economic activity which is represented by GDP per capita and material intensity, defined as material used per unit of GDP, is analyzed to derive the correlation parameters of an inverted U-shaped curve with the curve depicting the material needs of an economy in different economic phases (van Vuuren, 1999; de Vries et al., 2006).

Table 5-2 shows the demand drivers and key modeling parameters in the six models that have a representation of the non-metallic minerals or cement industry. POLES, DNE 21+, IMAGE, and TIAM-UCL relate the material demand to economic drivers. Some of the models that do not explicitly model physical demand of the cement industry start with directly estimating the energy demand of the sector using production functions. Different types of production functions are used in models assessing climate policies with varying elasticities of substitution (van der

Werf, 2008). In this type of modeling, energy efficiency is typically represented by the substitution between capital, material, labor, and energy inputs.

Table 5-2 Demand drivers in energy models and key cement modeling parameters (Edelenbosch et al., 2017)

Model	Demand	Technology/Energy use			
	Demand drivers	Production technology	Retrofitting options	Material efficiency	Technological change of individual production technologies
AIM-CGE	CES[a] production functions[1]	Yes[1]	Yes[2]	No	Yes (exogenously AEEI)[1,2]
DNE 21+	i) for low regional income levels cement production depends on total GDP ii) for high income levels depends on population size[7]	Yes[7]	Yes[6]	No[8]	Yes (exogenously)
GCAM	GDP	With or without CCS	No	No	Yes (exogenously)
IMAGE	Material demand is related to economic activity and material intensity	Yes	No[4]	Yes	Yes (exogenously; AEEI)
POLES	Material demand is related to economic activity and material intensity	Yes	Yes[5]	No	Yes (exogenously)
TIAM-UCL	GDP and other economic activity for energy or material demand	Yes	Only CCS[3]	No	Yes (exogenously, AEEI=1%)[3]

[a] CES (constant elasticity of substitution)

[1] Fujimori et al., 2014; [2] Babiker et al., 2001; [3] EFDA, 2004; [4] Gernaat David, personal communication; [5] IPTS, 2003; [6] ADVANCEwiki; [7] RITE, 2009.

After the cement demand is determined, an energy intensity value (i.e. as GJ/tonne cement) is usually used to estimate energy demand of the sector. The energy intensity can be based on the type of production technologies used and other important parameters such as the clinker content in cement while in other models an average value is used. Production technologies are represented in four models and retrofitting technologies in two models. In addition, the more efficient use of materials is only taken into consideration by one model explicitly (see Table 5-2). Modeling the physical demand instead of the energy demand allows for the inclusion of several industry characteristics such as explicit technology representation, material efficiency, retrofitting options therefore allowing for better understanding how sector specific policies can contribute to mitigation.

5.3 Information as input to long-term models

5.3.1 Areas of modeling improvements

Based on the overview of the current state of cement industry representation (section 5.2), we identify several areas where bottom-up information could be used for long-term energy modeling:

- modeling cement demand instead of directly modeling the energy demand;
- disaggregating the non-metallics sector to increasing the inclusion of bottom-up information on production technologies on a regional level;
- accounting for material efficiency (clinker to cement ratio);
- retrofit options.

While the modelling guide in Appendix 5B describes methods to develop a basic cement model which includes projecting cement demand and production technology information (the first two suggested improvements), here we focus on i) retrofitting with energy efficiency measures and ii) reducing the clinker content in cements based on the availability of supplementary materials. Improvements in energy efficiency can significantly decrease the industry's GHG emissions but in order to develop efficient climate policies, understanding how this energy efficiency can be achieved is crucial. Boyd and Zhang (2013) have shown in their analysis of the U.S. cement industry that two mechanisms play a role. Besides the energy efficiency gains from stock turnover (the replacement of old equipment with new which is usually more efficient), there are also significant energy efficiency gains from retrofitting. As different policies can encourage different energy efficiency improvements, energy models should be able to correctly simulate the decision-making behavior when it comes to new equipment purchases or the retrofitting of older technologies (Worrell and Biermans, 2005).

- *Retrofitting.* Industrial equipment can be used for long periods that exceed their lifetimes. This is a crucial point as prolonging the use of outdated and inefficient equipment affects future trajectories and burns on the carbon budget. Retrofitting in this case will have an important role.
- *Reducing clinker content.* The clinker content in cement and its contribution to GHG mitigation is a key parameter often overlooked by many long-term energy models (see Table 5-2). As clinker production is responsible for the majority of energy consumption and CO_2 emissions, limiting the volumes of clinker produced by replacing clinker in cement with other cementitious materials, mostly by-products of the steel industry and coal-fired power plants, is a very efficient way to reduce the industry's environmental impact. How much steel will be produced in the future from primary iron and how much coal will be used for electricity generation will influence the availability of these materials and thereby the cement industry's emissions. Long-term energy models should be able to capture the relationship between the activities in other sectors with the potential environmental performance of the cement industry under different scenarios.

In the following two sections we discuss the option of retrofitting (5.3.1.1) and clinker to cement ratio modelling (5.3.1.2) in more detail.

5.3.1.1 Retrofitting

There are many technologies/measures that could be adopted by existing cement plants to reduce the energy use and CO_2 emissions (for details see Worrell et al., 2013). For a summary of the measures see Table 5-10 in Appendix 5A. The readily available information on the related investment costs, lifetimes, and potentials for energy savings per technology/measure can allow for the incorporation of retrofitting in energy models. The only additional parameter that needs to be defined is the implementation rate. The approach we followed to estimate the implementation rate per measure and per region is the following:

First, based on information on the main technologies used for clinker production per region (see Table 5-3), we determined the regional implementation rates of the main retrofitting technologies (i.e., “Conversion of long dry to preheater”, “Addition of precalciner or upgrade”, “Conversion of long dry to preheater precalciner”, “Conversion from wet to dry precalciner” and “Conversion from semi-wet to semi-dry to dry precalciner”).

Table 5-3 Kiln technologies used in the different regions in 2013 (WBCSD, 2014)

	Dry with preheater and precalciner	Dry with preheater without precalciner	Dry without preheater (long dry)	Semi wet/semi dry	Wet/shaft kilns
Europe[1]	48%	29%	10%	8%	6%
Africa	82%	11%	2%	0%	4%
Asia & Oceania (excl. China, India and CIS)	91%	9%	0%	0%	0%
Brazil	100%	0%	0%	0%	0%
Central America	69%	31%	0%	0%	0%
China[2]	90%	0%	0%	0%	10%
CIS[3]	4%	4%	4%	3%	85%
Middle East	88%	12%	0%	0%	0%
North America	61%	18%	12%	0%	9%
South America (excl. Brazil)	67%	33%	0%	0%	0%
India	100%	0%	0%	0%	0%

[1] Assumed the same shares with EU28 reported in WBCSD (2014).

[2] (Yan et al., 2015).

[3] Year 2005 (European Union, 2009). In 2005, the dry kiln technology accounted for 12% of clinker production in 2005. Due to the lack of more detailed data, this share was split equally between the three different technologies shown in this Table.

Second, to determine implementation rates of the remaining technologies, for which there is limited information on current adoption rates, we compared the fuel intensity of Best Available Technology (BAT) with the current energy intensity in each region (seen in Figure 5-1) and calculated the technical energy savings potential for the base year. We then estimated the energy savings in each region, based on the implementation rates of the five main technologies listed in the previous paragraph and the typical energy savings they can offer (see Table 5-10 in Appendix 5A). We then deducted these energy savings from the technical energy savings potential to estimate the remaining energy savings potential that can be achieved with technologies other than the main five. The implementation rates for each of these technologies are estimated based on expert knowledge from industry. Table 5-11 in Appendix 5A shows the estimated implementation rates per technology and per region for 2010.

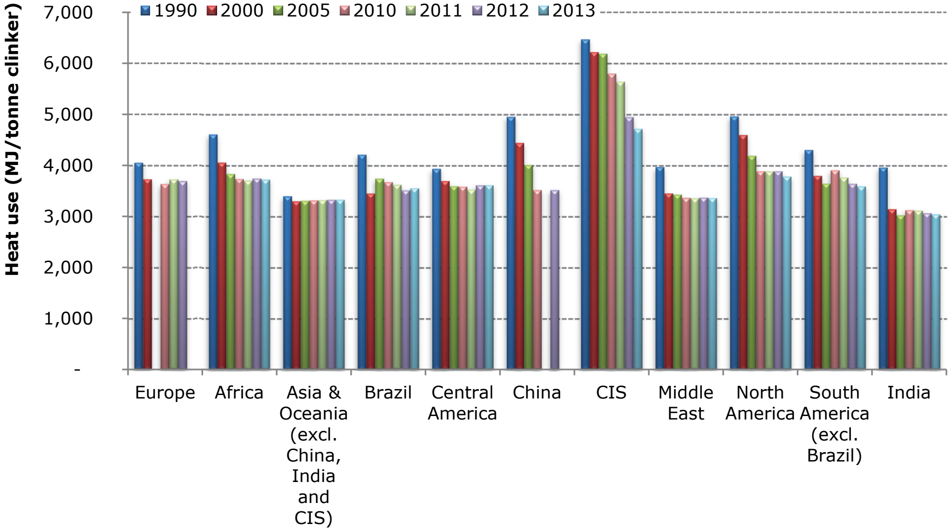

Figure 5-1 Heat consumption for clinker making per region (WBSCD, 2014; Xu et al., 2012). Heat use for fuel drying is not included

Table 5-4 shows the estimated energy savings per technology and per region along with the Cost of Conserved Energy (CCE) for a discount rate of 30%.

Table 5-4 Estimated energy savings per different measure and region for 2010 (discount rate=30%) (unit: MJ/tonne clinker)

Energy Efficiency Measure for Clinker Production	Europe	Africa	Asia & Oceania	Brazil	Central America	China	CIS	Middle East	North America	South America	India	CCE ($/GJ)
Energy Management and Control Systems	27	68	34	41	27	27	14	27	27	41	20	0.1
Kiln Combustion System Improvements	11	110	22	88	66	44	22	44	66	77	33	N/A
Mineralized Clinker	4	8	8	8	8	4	4	8	8	8	2	0.4
Indirect Firing	9	19	19	19	19	9	9	19	19	19	4	2.4
Oxygen Enrichment	7	15	15	15	15	7	7	15	15	15	3	1.8
Mixing Air Technology (PH kilns)	9	18	18	18	18	9	9	18	18	18	4	0.4
Seal Replacement	3	3	3	3	3	3	1	3	3	3	1	N/A
Kiln Shell Heat Loss Reduction	15	120	60	120	105	60	30	75	90	120	15	0.1
Preheater Shell Heat Loss Reduction	1	8	7	8	7	7	2	5	7	7	2	0.1
Refractories	0	0	0	0	0	0	0	0	0	0	0	0.2
Conversion to Grate Cooler	58	87	58	87	58	58	58	58	58	58	35	3.7
Upgrade Clinker Cooler	22	22	22	22	22	22	22	22	22	22	13	0.1
Optimize Grate Cooler	32	74	84	74	84	37	84	84	84	84	13	0.4
Low-Pressure Drop Suspension Preheaters	0	0	0	0	0	0	0	0	0	0	0	1.5
Heat Recovery for Power Generation	0	0	0	0	0	0	0	0	0	0	0	3.0
Conversion of Long Dry to Preheater	0	0	0	0	0	0	0	0	0	0	0	11.6
Increase Preheater Stages (from 5 to 6)	10	30	20	30	20	20	20	20	20	20	10	1.3
Addition of Precalciner or Upgrade	140	55	45	0	150	0	19	59	85	161	0	4.5
Conversion of Long Dry Kiln to Preheater Precalciner	119	30	0	0	0	0	49	0	151	0	0	8.7
Conversion from Wet to Dry precalciner Kiln	174	117	0	0	0	280	1,624	0	253	0	0	16.6
Conversion from Semi-Wet Semi to Dry precalciner Kiln	119	0	0	0	0	0	47	0	0	0	0	8.3
Total Savings	770	791	423	541	610	597	2,031	465	934	661	164	

5.3.1.2 Clinker to cement ratio

Portland cement has a clinker to cement ratio of 95-100% (the remaining part is gypsum). Substituting a part of clinker with other materials with similar properties (hydraulic and/or pozzolanic) reduces the clinker content in cement lowering the demand for clinker. Reducing clinker production by 1 tonne will roughly reduce CO_2 emissions by the same amount. Cements that contain clinker substituting materials in considerable quantities are known as blended cements. These materials are either interground with clinker in the final step of cement making[48] or are ground and dried separately before being mixed with clinker. Estimations on the availability of SCMs are shown in Table 5-6.

Materials widely used to replace clinker are:

- **Granulated Blast Furnace Slag (GBFS)**. Blast furnace slag (BFS) is a by-product of the iron steel industry. It is formed when iron ore is reduced in blast furnaces to produce pig iron (molten iron). For every tonne of pig iron produced 0.25-0.30 kg of BFS are formed (USGS, 2002). BFS can be distinguished based on the cooling method used into granulated, air-cooled and pelletized. When finely ground, ground granulated blast furnace slag (GGBFS) develops strong hydraulic cementitious properties (USGS, 2002), therefore suitable as clinker replacement in blended cements. Air-cooled blast furnace slag (ACBFS) on the other hand, is not suitable for use in cements and is mainly used as an aggregate in construction activities. Pelletized slag is usually used as lightweight aggregate but when finely ground can have similar cementitious properties to GGBFS (USGS, 2015). About 75% of world BFS production is currently granulated (Zeynel, 2014). It is estimated that in 2014, BFS production amounted to 325 Mtonnes (see Table 5-6). The BFS cements can contain up to 95% slags (IPTS/EC, 2010), however technically (current practice) the content ranges between 30 and 70% (ECRA, 2009).

- **Fly ash.** Fly ash is generated when coal is burned in furnaces. Fly ash can be of i) siliceous (silica-rich) or ii) calcareous (lime-rich) nature and has pozzolanic properties (ECRA, 2009; Harder, 2003). Calcareous fly ash may also have hydraulic properties. In Europe, because calcareous fly ashes can have strong variations in chemical composition and high sulfate content, the fly ash mostly used is of siliceous nature. Siliceous fly ash is generated in hard coal-fired power plants (Harder, 2003) (i.e. bituminous and anthracite coal). Not all fly ash can be used in cement production (VDZ and Penta, 2008). For both siliceous and calcareous fly ash certain criteria need to be met.

The amounts of fly ash generated depend on the coal quality and the technologies in place. For every tonne of coal burnt 0.07-0.30 tonnes of fly ash are generated (based on ACAA, 2012 and U.S EIA, 2016; Lan and Yuansheng, 2007). Table 5-5 shows our estimates of the fly ash production in a number of regions/countries.

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[48] These substitutes can either be used to replace clinker in the cement or the concrete mix (product change) or can be introduced in the kiln feed (feedstock change) to replace limestone.

Fly ash cements can have a fly ash content of 6-55% (siliceous). In technically used cements the fly ash content is in the range of 25-35% (ECRA, 2009).

- **Pozzolanas.** Pozzolanas are materials of mainly siliceous nature that can either occur naturally or be developed artificially. Natural pozzolanas are materials of volcanic origin or sedimentary rocks such as pumice and pumicite. The world production in 2013 of pumice and other natural pozzolanas was estimated at 18.6 Mtonnes (USGS, 2015). Artificial pozzolanas, or else known as calcined natural pozzolanas, are materials with pozzolanic properties that need to be calcined in kilns. Some examples are calcined clays, calcined shale and metakaolin (Kosmatka et al., 2002). The global production of artificial pozzolanas is hard to estimate. Other materials with pozzolanic properties are rice husk ash and silica fume. Rice husk is a byproduct of the rice industry commonly burnt or discarded as waste (Koteswara et al., 2012). It is estimated that in 2014 about 10 Mtonnes of rice husk were produced, with which 27 Mtonnes of ash could be generated. Silica fume is a silica-rich byproduct of the silicon alloy production industry available only in limited quantities.

According to the European standard EN 197-1, cements containing 6-65% pozzolanas are possible; however, in currently used cements the mass content is limited to 15-35% (Kosmatka et al., 2002; ECRA, 2009). For pozzolanas that do not require calcination the decrease in energy use and CO_2 emissions from clinker replacement is almost linear to the increase in pozzolana use. If artificial pozzolanas are used the energy use from pozzolana calcination and the associated CO_2 emissions must be taken into account.

- **Limestone.** Another way to reduce the clinker content in cements is by adding limestone. Limestone is widely available to cement plants as it is the main raw material used in cement production. Limestone is typically used in cements as a minor constituent (up to 5%) for increased workability. Higher limestone quantities however could also be used. The limestone content in cement could be as high as 25-35% (ECRA, 2009). For limestone cements to show similar strengths with ordinary Portland cement (OPC) the particle fineness needs to increase. The properties of limestone cements with up to 15% limestone content can be compared to OPC (PCA, 2014).

Table 5-5 Estimated fly ash production in the different world regions in 2011

Country/region	Coal consumption for el. generation Mtonnes[2]	Fly ash content in coal (tonne fly ash/tonne coal)	Fly ash production (Mtonnes)
Australia	89	0.13	11.8[1]
Canada	41[4]	0.08[3]	3.4
China	1,551	0.28[5]	429.6
Europe (15)	224	0.16[6]	35.4
India	400	0.27[7]	107.3
Japan	90	0.11[8]	9.9
United States	934[10]	0.07	66.0[9]
Russia	143	0.17[11]	25.6
Brazil	6	0.37[12]	2.1
Total	3,477	0.20 *(average)*	691
Rest *(23% of coal use)*	988	0.20 *(average)*	196
World	4,465	*0.20 (average)*	887

[1] CRC, 2012

[2] Unless otherwise mentioned, the volumes of coal consumed for electricity generation were estimated based on the coal use (in ktoe) reported in IEA statistics (IEA, 2015) and the typical gross calorific values (GCV) of each coal type (IEA, 2005).

[3] In 2006, Canadian power plants consumed about 51 Mtonnes of coal (Statcan, 2016) and generated 4.2 Mtonnes of fly ash (CIRCA, 2007).

[4] Statcan, 2016

[5] Chinese coal is characterized by high fly ash content that ranges between 0.25-0.3 tonnes/tonne coal (Lan and Yuansheng, 2007). Typically, Flue Gas Desulphurization Gypsum (FGD) produced during sulfur removal is not considered to be fly ash. However, that is the case in the Lan and Yuansheng (2007) analysis. To exclude FGD (primarily used in the production of gypsum) we subtract the 76.6 Mtonnes of FGD that was produced in coal-fired power plants in 2011 (Wang and Deng, 2015).

[6] In 2003, 44.1 Mtonnes of fly ash were generated in EU (15) (ECOBA, 2006). Based on the IEA statistics (2015), it is estimated that in 2003, 279 Mtonnes of coal were consumed for power generation. That leads to a factor of 0.16 tonnes of fly ash per tonne of coal consumed in coal-fired plants.

[7] In 2014/15, coal consumption in Indian coal-fired power plants reached 437 Mtonnes and coal ash production 145 Mtonnes (a 33.2% ash content) (Cea, 2015). This also includes bottom ash that accounts for about 20% of ash production (Senapati, 2011) resulting in about 27% fly ash content. This is in agreement with the annual volumes reported in other studies (Dhadse et al., 2008; Lokeshappa and Dikshit, 2011).

[8] In 2007, Japan generated 12 Mtonnes of coal ash (Moon, 2013). In Japan, 90% of coal ash generated is fly ash (Ishikawa, 2008). The same year about 98 Mtonnes of coal were consumed in power plants (estimated based on IEA, 2015); resulting in a factor of 0.11.

[9] ACAA, 2011

[10] U.S. EIA, 2016

[11] Average ash content (containing bottom ash) of coal used in Russian power plants is around 21% (Putilov and Putilova, 2015). Of which bottom ash usually accounts for 20-25% (Heidrich et al., 2013).

[12] According to Moon (2013), Brazilian plants consume annually 37 Mtonnes of coal and generate 17 Mtonnes of fly and bottom ash. Usually bottom ash accounts for 20-25% of total ash production. We therefore estimate a fly ash content of 0.37.

Table 5-6 Estimated annual production of supplementary cementitious materials

Supplementary Cementitious Materials (SCMs)	Estimated Annual Production (Mtonnes)	Production factor
Blast Furnace Slag[1]	296-355 (in 2014)	0.25-0.30 kg BFS/tonne pig iron (USGS, 2003); 0.275 kg BFS/tonne crude steel produced with the BF/BOF route (Worldsteel, 2014)
Granulated BFS	222-266	-
Fly Ash[3]	720-865 (in 2012)	depends on coal quality (see Table 5-5)
Hard coal fly ash[2,3]	570-690 (in 2012)	-
Natural Pozzolanas	18.6 (in 2013)	
Volcanic ash	0.5	-
Pumice	2.9	-
Pozzolanas	6.6	-
Unspecified	8.6	-
Artificial Pozzolanas	N/A	-
Other Pozzolanas	~ 42.5	
Rice husk ash	27 (in 2014)	5.5 kg rice husk ash per tonne rice paddy milled (Koteswara et al., 2012)
Silica fume	< 1.5 (in 2008)	0.1-0.25 tonnes per tonne quartz (Fidjestøl and Dåstøl, 2008)
Total (excl. artificial pozz.)	862-1,050	

[1] BFS production data are not available. The volumes were estimated based on the production factors reported and global pig iron production for 2014 (1,183 Mtonnes) (Worldsteel statistics).

[2] Only fly ash generated from coal-fired power plants. Estimated based on coal consumption data for electricity generation reported in 2014 IEA statistics (IEA, 2015) and the average production factor shown in Table 5-5.

[3] Fly ash formed in power plants using anthracite and bituminous coal.

5.4 Modeling approach

5.4.1 Accounting for retrofitting

In the following paragraphs we present three ways for incorporating retrofitting in energy models.

i) Cost-supply curves.

Cost-supply curves are a useful tool that is used to present the cost-effective as well as the technical energy and GHG savings potentials of several energy efficiency measures. To construct the curves, the energy and GHG emission mitigating measures/technologies are ranked based on their Cost of Conserved Energy (CCE), or Cost of Mitigated Greenhouse Gases ($C_{CO2\text{-eq}}$). The cost-supply curves show in the y-axis the CCE and in the x-axis the cumulative energy savings and the cumulative GHG emission savings. The width of each segment in the graph shows the energy or GHG savings potential of each energy efficiency improvement measure.

The CCE can be determined with the use of Eq. 5-1 and Eq. 5-2, respectively.

$$CCE = \frac{Annualized\ investment\ cost + Annual\ O\&M\ costs}{Annual\ energy\ savings} \qquad (5\text{-}1)$$

The annualized investment cost is a function of the discount rate and the technical lifetime of the technology and can be calculated from Eq. 5-2.

$$Annualized\ investment\ cost = \ Investment\ cost \times \frac{d}{(1-(1+d)^{-n})} \qquad (5\text{-}2)$$

Where d is the discount rate and n the technical lifetime of the measure.

Long-term energy models typically estimate future energy prices based on technology development, regional resource availability and trade. Certain measures that are found to be cost-effective in one country/region might not be cost-effective in another due to regional price differences. This effect can be represented by cost-supply curves, where an increase in energy prices due to for example policy measures, will for some measures result in switching from non-cost-effective to cost-effective. In addition, the energy prices for which important energy efficiency measures become cost-effective can be determined.

ii) Payback period (PBP)

Another way of incorporating technological detail could be by estimating the Payback period (PBP) for every measure. All measures can then be ranked based on their PBP and the measures with the lowest PBP can be implemented first (Eq. 5-3).

$$PBP = \frac{Initial\ investment}{Annual\ opreational\ benefits - Annual\ operational\ costs} \qquad (5\text{-}3)$$

iii) Step function

The wide range of energy efficiency measures could also be clustered based on the required investments costs into a) low investment measures, b) medium investment measures, and c) high investment measures. The model can then use a step function and assess the reduction in energy consumption.

In addition, the measures could be clustered in the measures for each key process; i.e. clinker and cement making. Low investment measures are measures that will typically have a PBP of less than 3 years, medium investment measures are measures with a PBP of 3-5 years and high investment measures are measures with a PBP higher than 5 years. All approaches should take into account the potentials for technology implementation in each region (see Table 5-11 in Appendix 5A).

5.4.2 Endogenously determining the clinker to cement ratio

By linking the availability of key SCMs to the output of other sector modules within the model, the clinker to cement ratio could be modeled endogenously. More specifically, for long-term energy models that model steel production and electricity production from coal-fired power plants process explicitly, the availability of GBFS can be linked to primary steel production and the availability of fly ash to the activity of coal-fired power plants.

A simplified way to estimate the potential for energy savings and GHG abatement that an increased use of clinker substituting materials could achieve, can be to only consider the availability of the main raw materials. In this way, the relationship between the activity of the main SCM sources and the cement industry are captured. In reality, the development of the clinker content in cement in the various world regions can be very hard to forecast, as the use of SCMs does not depend only on their availability but also on a number of other important parameters (ECRA, 2009); i) prices of clinker substitutes, ii) national standards, iii) market acceptance and iv) cement properties.

Modelling using the above described approach does give an approximation of the technical potential. This assumes that the cement industry consumes all available clinker substituting materials under the restrictions that:

- Blast Furnace Slag (BFS) cement can contain up to 65% BFS;
- Fly Ash cement can contain up to 35% fly ash;
- Limestone cement can contain up to 15% limestone;
- Blended cements cannot contain more than one clinker substituting material.

Because the actual availability/reserves of pozzolanas is/are hard to quantify we do not consider pozzolana cement production in this study. In addition, we do not allow for the production of blended cements that contain more than one type of clinker substituting materials. This is because it would be hard to restrict the levels of the different materials that could be used for a widely acceptable cement quality.

To determine the shares of the different cement types in an effort to estimate the clinker production for each region if all available clinker substitutes are consumed we follow the following allocation approach:

First, we determine the potential for BFS cement production based on the generation of BFS from steel plants operating blast furnaces under the restriction that BFS cement can contain up to 65% BFS. We then determine the amount of fly ash cement that is generated, with the restrictions that fly ash cement can contain up to 35% fly ash and that BFS cement does not contain fly ash. All remaining cement is limestone cement with 15% limestone. For all cement types we assume that minor constituents account for 5% of the overall weight. The total production of clinker will be equal to the sum of clinker contained in BFS cement, in fly ash cement and in limestone cement.

$$P_{clinker} = CC_{BFS\ cement} * P_{BFS\ cement} + CC_{Fly\ Ash\ cement} * P_{Fly\ Ash\ cement} + CC_{Limestone\ cement} * P_{Limestone\ cement} \quad \text{(Eq. 5-4)}$$

Based on the allocation approach described above, Eq. 5-4 can be re-written into:

$$P_{clinker} = CC_{BFS\ cement} * \frac{C_{BFS}}{BFS.C_{BFS\ cement}} + CC_{Fly\ Ash\ cement} * \frac{C_{Fly\ Ash}}{Fly\ Ash.C_{Fly\ Ash\ cement}} + CC_{Limestone\ cement} * \left[P_{cement} - \frac{C_{BFS}}{BFS.C_{BFS\ cement}} - \frac{C_{Fly\ Ash}}{Fly\ Ash.C_{Fly\ Ash\ cement}}\right] \qquad \text{(Eq. 5-5)}$$

Where, $\boldsymbol{P_{BFS\ cement}} = \frac{\boldsymbol{C_{BFS}}}{\boldsymbol{BFS.C_{BFS\ cement}}}$, $\boldsymbol{P_{Fly\ Ash\ cement}} = \frac{\boldsymbol{C_{Fly\ Ash}}}{\boldsymbol{Fly\ Ash.C_{Fly\ Ash\ cement}}}$, and $\boldsymbol{P_{Limestone\ cement}} = \frac{\boldsymbol{C_{BFS}}}{\boldsymbol{BFS.C_{BFS\ cement}}} - \frac{\boldsymbol{C_{Fly\ Ash}}}{\boldsymbol{Fly\ Ash.C_{Fly\ Ash\ cement}}}$.

Table 5-7 Variable definitions - Equations 5-4 and 5-5

Parameters	Definition	Unit	Value
$\boldsymbol{BFS.C_{BFS\ cement}}$	BFS content in BFS cement	%	65% (fixed value)
$\boldsymbol{C_{BFS}}$	BFS consumed in the cement industry	Mtonnes BFS	Calculated with Eq. 5-6
$\boldsymbol{CC_{BFS\ cement}}$	Clinker content in BFS cement	%	30% (fixed value)
$\boldsymbol{CC_{Fly\ Ash\ cement}}$	Clinker content in fly ash cement	%	60% (fixed value)
$\boldsymbol{CC_{Limestone\ cement}}$	Clinker content in Limestone cement	%	80% (fixed value)
$\boldsymbol{C_{Fly\ Ash}}$	Fly ash consumed in the cement industry	Mtonnes Fly Ash	Calculated with Eq. 5-8
$\boldsymbol{Fly\ Ash.C_{Fly\ Ash\ cement}}$	Fly ash content in fly ash cement	%	35% (fixed value)
$\boldsymbol{P_{BFS\ cement}}$	BFS cement production	Mtonnes BFS cement	
$\boldsymbol{P_{cement}}$	Cement production	Mtonnes cement	Model output
$\boldsymbol{P_{Fly\ Ash\ cement}}$	Fly Ash cement production	Mtonnes Fly Ash cement	
$\boldsymbol{P_{clinker}}$	Clinker production	Mtonnes clinker	
$\boldsymbol{P_{Limestone\ cement}}$	Limestone cement production	Mtonnes Limestone cement	

The amount of BFS consumed in the cement industry (C_{BFS}) can be calculated with Equation 5-6:

- If $P_{cement} < {}^{P_{BFS}}/_{BFS.C_{BFS\ cement}}$, then $C_{BFS} = {}^{BFS.C_{BFS\ cement}}/_{P_{cement}}$

(Eq. 5-6)

- If $P_{cement} > {}^{P_{BFS}}/_{BFS.C_{BFS\ cement}}$, then $C_{BFS} = P_{BFS}$

Where the BFS production (P_{BFS}) can be calculated with Equation 5-7:

$$P_{BFS} = P_{steel,total} * Share_{primary\ route} * C_{pig\ iron} * I_{BFS} * I_{iron} \qquad \text{(Eq. 5-7)}$$

Table 5-8 Variable definitions - Equations 5-6 and 5-7

Parameter	Definition	Unit	Value
$\boldsymbol{P_{BFS}}$	BFS production	Mtonnes BFS	
$\boldsymbol{P_{steel,total}}$	Total steel production	Mtonnes Steel	Model output
$\boldsymbol{Share_{primary\ route}}$	The share of steel produced with the primary route (i.e. from iron ore in the blast furnaces).	%	Model output
$\boldsymbol{C_{pig\ iron}}$	The percentage input of pig iron in blast furnaces	%	Model input (fixed value in IMAGE=90%)
$\boldsymbol{I_{BFS}}$	The amount of BFS generated per tonne of pig iron used in blast furnaces	Tonne BFS/tonne pig iron	0.275 (fixed value)
$\boldsymbol{I_{iron}}$	Specific iron requirements per tonne of crude steel generated	Tonne iron/tonne steel	Model input

The amount of fly ash consumed in the cement industry ($C_{Fly\ Ash}$) can be calculated with Equation 5-8.

- If $P_{cement} - \boldsymbol{P_{BFS\ cement}} < {}^{P_{Fly\ Ash}}\!/_{Fly\ Ash.C_{Fly\ Ash\ cement}}$, then (Eq. 5-8)

$$C_{Fly\ Ash} = Fly\ Ash.C_{Fly\ Ash\ cement} * (P_{cement} - \boldsymbol{P_{BFS\ cement}})$$

- If $P_{cement} - \boldsymbol{P_{BFS\ cement}} < {}^{P_{Fly\ Ash}}\!/_{Fly\ Ash.C_{Fly\ Ash\ cement}}$, then $C_{Fly\ Ash} = P_{Fly\ Ash}$

Where, $P_{Fly\ Ash}$ is given by Eq. 5-9:

$$P_{Fly\ Ash} = Coal_{powerplants} * I_{fly\ ash} \qquad \text{(Eq. 5-9)}$$

Table 5-9 Variable definitions - Equations 5-8 and 5-9

Parameter	Definition	Unit	Value
$\boldsymbol{P_{Fly\ Ash}}$	Fly ash production from power plants	Mtonnes fly ash	
$\boldsymbol{Coal_{powerplants}}$	Coal consumption in power plants	Mtonnes coal	Model output
$\boldsymbol{I_{fly\ ash}}$	The amount of fly ash generated per tonne of coal consumed in power plants	Tonne fly ash/tonne coal	Differs per region (see Table 5-5)

5.5 Implementation of the bottom-up information in IMAGE

In this section, we evaluate the model results after the implementation of the two suggested improvements. The section is divided into two parts. The first part shows the impact the inclusion of energy efficiency retrofitting on the model results, while the second part focuses on the impact the dynamic modeling of the clinker to cement ratio. For the comparison of the cement industry projections, we look into *two scenarios:*

1. without new climate policies (“baseline scenario”) and;
2. aiming at a stabilization level at 450 ppm CO_2-eq (“mitigation scenario”).

In both cases, we present the data before (“original”) and after (“improved”) including the improved bottom-up information.

5.5.1 Energy efficiency retrofitting

Previously in IMAGE, when new plants were built either because capacity increased in a specific region or because old plants were decommissioned, the model chose between four technology types (“conventional dry plant”, “efficient dry plant”, and two technologies of “efficient dry with Carbon Capture and Storage (CCS)”). Although the model dealt with stock turnover, it did not deal with energy efficiency improvements in existing cement plants. Based on the method described in Section 5.3.1 using available information on current regional technology adoption levels and on energy savings and investment costs per measure, the model can estimate the impact of retrofitting on the energy consumption. In this way, the “low-regret” measures that are usually not taken into account in energy models are also considered. The scenarios that include retrofitting are named “baseline improved” and “mitigation improved”. In the “mitigation improved” scenario the same carbon tax is applied that was applied in the original scenario to meet a 450 ppm target.

Figure 5-2, shows the projected global fuel use, CO_2 emissions, fuel intensity, and regional energy savings before and after taking into account retrofitting. When retrofitting is considered, the energy demand under both scenarios, the baseline and the mitigation scenarios, is lower during the 2010-2040 period. It can be seen that for the upcoming period, there exists a non-negligible potential for energy savings from retrofitting. Overall, the overall energy consumption can be reduced by 9.8 EJ in the baseline improved scenario and by 11 EJ in the mitigation improved scenario. After 2040, retrofitting does not play a role. This is because, no old inefficient plants will be in operation and all new plants that have been added either to cover the increasing cement demand or to replace decommissioned plants were considered in the model to be high efficient state-of-the-art plants. However, if new efficient technologies become available in the future, retrofitting could further reduce the energy use. Emerging/innovative retrofit technologies were not considered in this analysis.

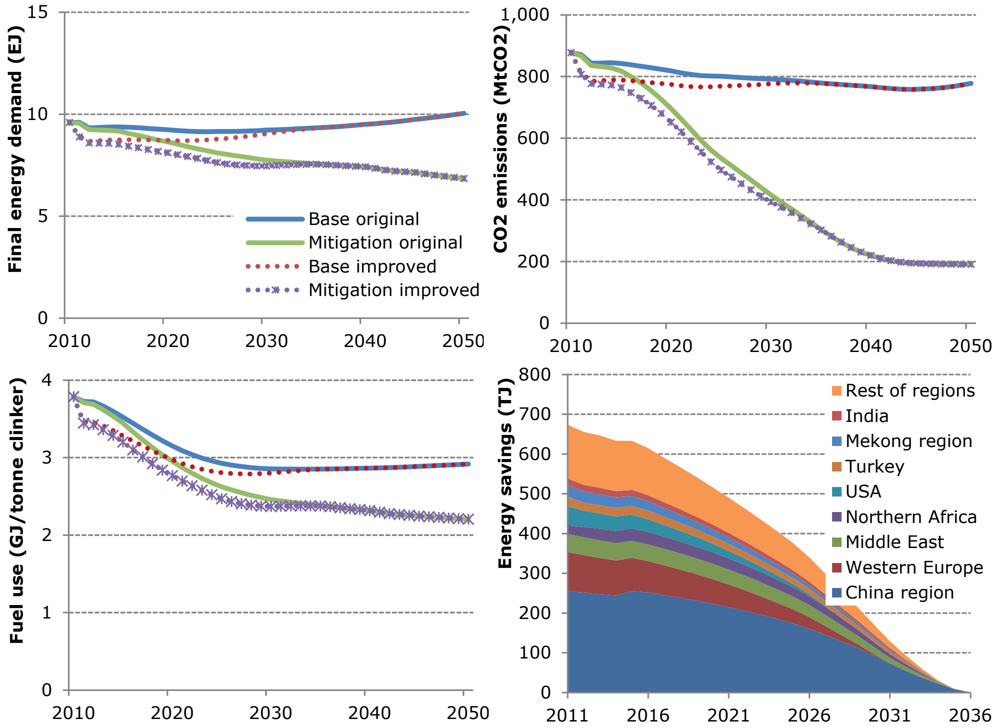

Figure 5-2 Global energy use, CO_2 emissions, fuel intensity, and regional energy savings for cement production before and after taking retrofitting with energy efficient technologies into account under the baseline and mitigation scenario

After 2020, the total energy use in the baseline original scenario is projected to face a gradual increase as a result of the increasing clinker production. Although the global average fuel intensity decreases due to energy efficiency improvements implemented, the absolute energy consumption continues to increase until 2070. After 2070, the overall energy consumption experiences a small annual decrease due to the projected slowdown in clinker production. In 2020, retrofitting can reduce the fuel use for clinker production from 3.2 to 3.0 GJ/tonne clinker in the baseline improved scenario. In the mitigation improved scenario, the fuel intensity drops considerably due to the uptake of innovative energy efficiency technologies. When a carbon price is introduced as a climate policy measure (mitigation scenarios) the energy use after 2050 increases dramatically due to the uptake of CCS.

Retrofitting can reduce the total CO_2 emissions generated in the period 2010-2040 by 853 Mt CO_2 under the baseline improved scenario and by 917 $MtCO_2$ under the mitigation improved scenario (see Figure 5-2).

In the 'improved" scenarios only energy efficiency improvements considered "cost-effective" are adopted. The highest overall energy savings within the 2010-2040 period are to be found in the China region, Western Europe, Northern Africa and United States amounting to 43.3%, 11.3%, 5.3% and 4.1%, respectively. The Russian Federation has a large potential for energy savings from retrofitting as clinker is primarily produced in inefficient wet cement kilns. However, because the measures identified in Table 5-4 are not found cost-effective (energy prices are low) they are not implemented.

5.5.2 Clinker to cement ratio

In the baseline original scenario, the clinker to cement ratio experiences a modest decrease and from then onwards it gradually decreases to converge to 74% by 2050 for all regions. Figure 5-3 shows the impact that the modeling the clinker to cement ratio based on the method described in Section 5.3.1 has on clinker production, energy demand and CO_2 emission projections.

Taking into account the availability of SCMs and the maximum content of SCMs per blended cement type, clinker production can be limited to 2,620 Mtonnes in 2050; this is 15% lower compared to the baseline original scenario (3,100 Mtonnes in 2050). After reaching a maximum of 2,800 Mtonnes the clinker production decreases to 2,600 Mtonnes by 2100; about 22% lower compared to the baseline original scenario. This is due to the high fly ash availability. Figure 5-3 also shows the amount of coal consumed for power generation and the amount of steel produced with the primary route on a global scale in IMAGE. Under the baseline scenario fly ash production is projected to reach 14 Gtonnes by 2100.

In the mitigation original scenario clinker production is lower than in the baseline original scenario. In the original model formulation in IMAGE, the clinker to cement ratio is modelled dynamically to the carbon price, assuming that climate policy would lead to less clinker use where by 2100 the clinker to cement ratio drops to 65%. However, when taking into account the availability of BFS and fly ash under the same carbon tax (mitigation improved scenario) the clinker to cement ratio is higher due to the limited availability of SCMs. In this scenario the clinker production will reach 3,060 Mtonnes in 2050 and 3,340 Mtonnes in 2100, 9% and 14% higher when compared to the mitigation original scenario. This is the result of the decommissioning of many coal-fired plants and the increased use of renewable sources for power generation reducing the generation of fly ash. At the end of the century in the mitigation scenarios, coal consumption for electricity generation drops by 93%, with only about 890 Mtonnes of coal consumed for electricity generation (see Figure 5-3).

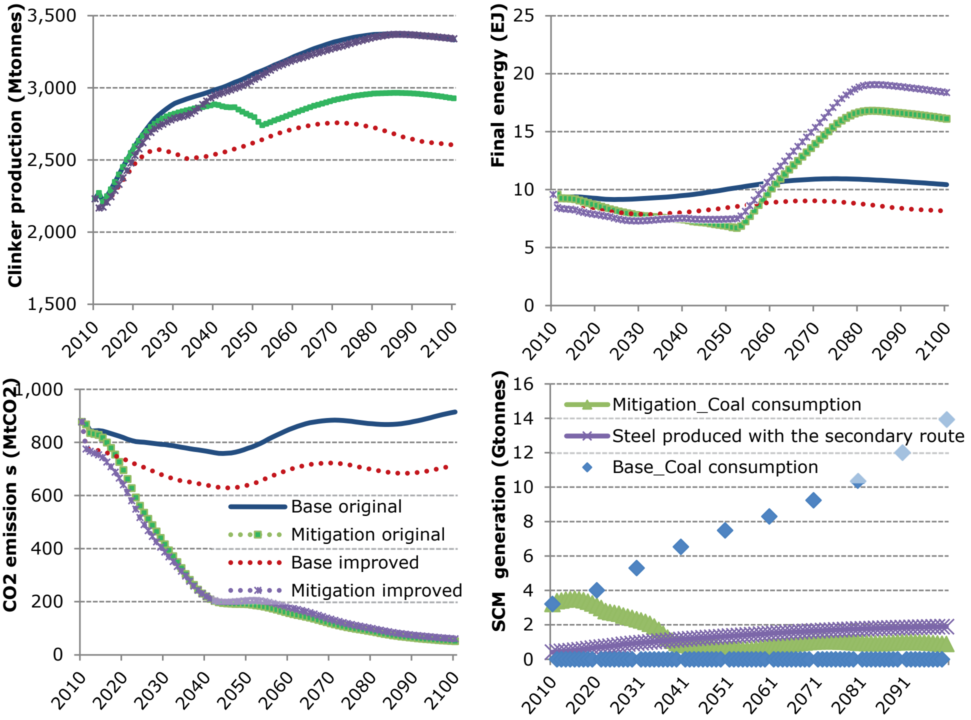

Figure 5-3 Clinker production before and after taking into account the regional SCM availability

In the baseline improved scenario, energy use is considerably lower than in the baseline original scenario. However, when taking into account the limited availability of SCMs the energy use is even higher. In the mitigation improved scenario the 2100 energy use is 14% higher when compared to the mitigation original scenario (see Figure 5-3). In 2100 and in the baseline improved scenario, the CO_2 emissions are 22% lower than in the baseline original scenario. Under both mitigation scenarios the CO_2 emissions are similar as CCS is employed to reduce the CO_2 emissions to a certain level. However, it should be noted that under the mitigation improved scenario the CO_2 emissions that need to be captured are considerably higher as more clinker is produced which translates into more emissions.

Using the methodology developed in this analysis allows for a better understanding of the impact of SCM availability on the cement composition across the world. Figure 5-4 shows the amounts of BFS and fly ash available in China and India but also the amounts of BFS and fly ash that can be utilized under the baseline improved and mitigation improved scenarios for 2050. Figure 5-9 in Appendix 5C shows the same results but for all 26 regions used in IMAGE.

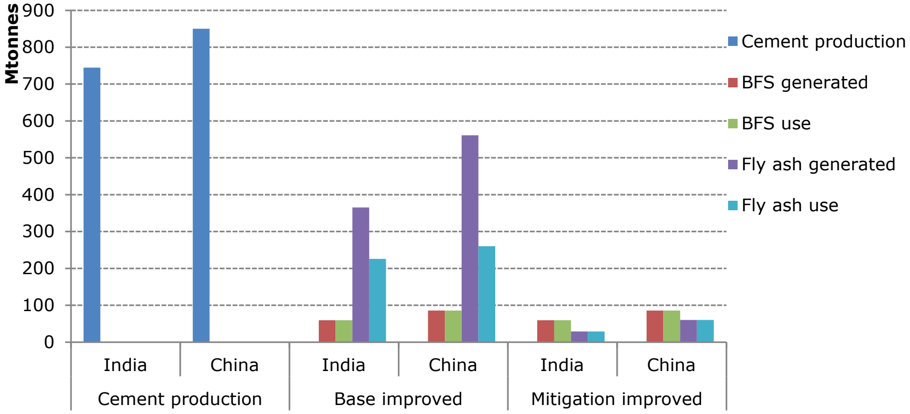

Figure 5-4 SCM availability and utilization in India and China in the a) baseline improved and b) mitigation improved scenarios in 2050

In this analysis, trade of SCMs is not included. When SCM availability is higher than the possible utilization, a part remains unexploited. For example, as seen in Figure 5-4 in the China region, about 560 Mtonnes of fly ash will be generated but only 260 Mtonnes is used in cement production. Similar is the case in India, South Africa, Central Europe, Ukraine region, Kazakhstan region, Russian Federation, Korea region, Japan, and Oceania. In total, 1,450 Mtonnes of fly ash are generated in 2050 of which 930 Mtonnes are used in blended cements. The majority of the remaining 520 Mtonnes fly ash is in China (58%) and in India (27%). If traded, it can be used by other regions to lower the clinker to cement ratio. In such a case 390 Mtonnes could be used by the other regions.

BFS is only available in lower quantities. In 2050, 293 Mtonnes of BFS become available globally and are all used in blended cements. As shown in Figure 5-4, in the mitigation improved scenario, fly ash is no longer available in large quantities. In 2050, about 140 Mtonnes become available and are all utilized. The amount of BFS available remains the same.

Figure 5-5 shows the cement composition under the two scenarios for 2050 in the major cement producing regions. The cement composition for all 26 regions used in IMAGE for 2050 and 2100 can be seen in Appendix 5D. In the baseline improved scenario, the global average clinker to cement ratio is estimated at 62%. In the mitigation improved scenario, the global average clinker to cement ratio is estimated at 73%. The limited availability of fly ash is visible. Limestone in the mitigation improved scenario is used in greater quantities as less of the other SCMs are available. In this study limestone cement is limited to 15%.

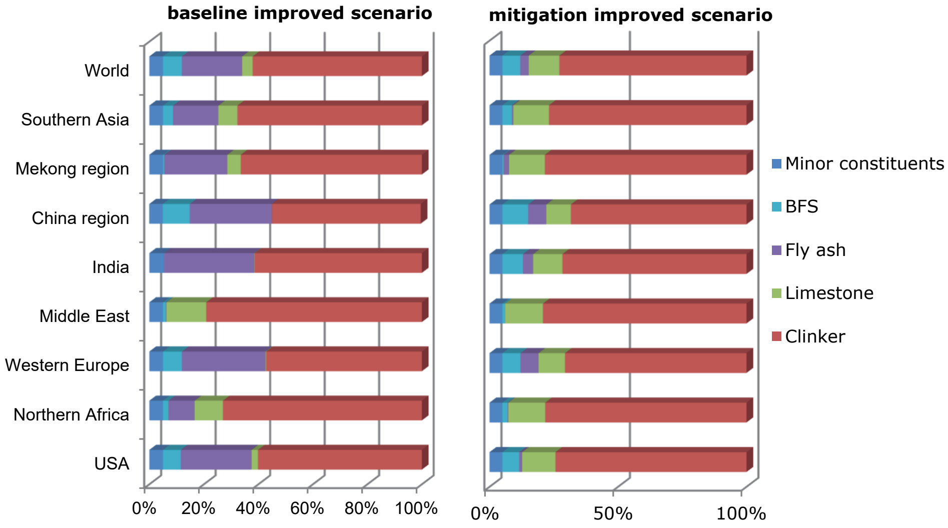

Figure 5-5 Cement composition in 2050 under the a) baseline improved and the b) mitigation improved scenarios.

5.6 Discussions and conclusion

5.6.1 Scope for adding bottom-up detail to long-term energy models

This analysis has shown that both the inclusion of retrofitting with energy efficient technologies/measures and the modeling of the clinker content in cement that considers the availability of SCMs have an important impact on model results.

When retrofitting is taken into account, many measures/technologies are identified as cost-effective and consequently adopted, lowering the energy use for cement making for the relatively short term. Retrofitting can save 9.8 EJ of energy globally within the period 2010-2035 in a baseline scenario, while in a mitigation scenario 11 EJ of energy can be saved (4 and 5% of overall CO_2 emissions within this period).

When the availability of SCMs is taken into account, mainly BFS and fly ash, in a mitigation scenario, the potential for clinker to cement ratio reduction is significantly narrowed down. This is because in a mitigation scenario, many coal-fired power plants are considered to shut down resulting in a dramatic decrease in fly ash availability. In this analysis, in the mitigation improved scenario, clinker production will reach 3,060 Mtonnes in 2050 and 3,340 Mtonnes in 2100, 9% and 14% higher when compared to the mitigation original scenario resulting in higher energy consumption.

To improve the representation of the cement industry in energy models and better identify the energy and GHG savings that i) energy efficiency and ii) material efficiency (in this analysis restricted only to clinker substitution) can offer, it is important to take into account key industry characteristics. For energy efficiency it is important to consider the extent to which energy efficiency improvements have already been adopted in certain regions and identify the remaining energy efficiency potential that has not been captured so far. For material efficiency it is important to consider that mitigation policies in other areas of the model, in this case in the energy sector, can affect the GHG mitigation potential of material efficiency in the cement industry.

We have shown that it is possible to incorporate a relatively simple modeling approach for retrofitting and dynamic modeling of the clinker to cement ratio based on bottom-up available information in energy models.

The developed modeling approach still has certain limitations, mostly as result of the required simplifications:

Utilization rate of SCMs: In this analysis, the regional availability and certain restrictions on the level of technical SCM to cement ratio (depending on the SCM type) determine the level of utilization. However, more parameters such as product and national standards, price and trade of SCMs can impact the utilization rate. To model all these factors on a regional level for the near and distant future is complex and uncertain.

Trade of SCMs: If trade of SCMs was also included, the 520 Mtonnes of unexploited fly ash identified for 2050 under the baseline improved scenario, can be used by other regions. However, due to restrictions on the fly ash content of fly ash cement (fly ash content can be 35%) only 390 Mtonnes can realistically be used by the other regions. The utilization of the left-over fly ash would decrease the clinker to cement ratio from 62% to 57% as fly ash cement has higher content in SCMs than limestone cement.

Variety of SCMs: This study only took into account the use of BFS, fly ash and limestone as clinker replacements in cement. However, pozzolanas, either natural or artificial, could also be used to further reduce the clinker to cement ratio. Currently, the annual pozzolana production is limited (see Table 5-6) and data on the actual regional availability/reserves of some natural pozzolanas, such as volcanic ash, is not available. Because of data limitations, the analysis was limited to these three materials.

Quality of SCMs: A main assumption in this analysis is on the quality of the available BFS and fly ash. To estimate the lowest possible clinker to cement ratio it was considered that all BFS and fly ash generated are of sufficient quality for use as clinker replacements. This means that all BFS is granulated (the current granulation level is about 75%) and that all fly ash available, is of sufficient quality for use in cements. Transforming however all generated fly ash to desired quality for use as SCM remains a challenge. If not all fly ash can be used, the clinker to cement ratio would be even higher under the 450 scenario.

Uncertainties: It is hard to determine the exact implementation rates for all energy efficiency technologies/measures shown in Section 5.3. To restrict the uncertainties on these figures we tried to base our estimates on reported information for the main measures offering the largest part of energy savings.

For each of the technologies/measures to be adopted a specific energy savings potential (GJ/tonne clinker) has been assigned (see Table 5-10 in Appendix 5A). This number is based on information concerning the U.S. industry. In reality, the energy saving potentials would be different for each region based on the average energy intensity for clinker production in that region. However, the difference is not expected to be large.

In this paper, we only analyzed energy efficient measures/technologies for clinker production with the dry process. The only option that was considered for energy efficient improvement in plants that operate wet, semi-wet or semi-dry kilns would be the switch to the dry process. In some cases, for example Russia, this switch was not identified as cost-effective and was not implemented under the baseline improved scenario. If the option of energy efficiency improvement measures specific to the wet process was also considered, some of these measures could be cost-effective and thereby decrease the energy use in these regions.

Another uncertainty lies on the amount of fly ash generated from coal-fired power plants in the various regions. In reality, the volumes of fly ash generated will depend on the quality of coal and the burning process and both can vary through time. In this analysis, we have assumed a fixed fly ash generation that only varies per region.

5.6.2 Conclusions

The industrial sector is complex, primarily due to the heterogeneity of products manufactured, e.g. chemicals and petrochemicals, cement, glass, metals such as steel and aluminium, that are all produced in different industrial processes. Each sector has its specific characteristics and dynamics. To better understand the decarbonization options under different climate policy scenarios for these high consumption industry sectors it is important to include the key industry sub-sector specific characteristics that affect its energy development. In this paper, we specifically focus on the cement sector, providing an overview of the state-of-the-art of cement sector modelling in IAMs, proposing ways for improvement, and testing these in the IAM IMAGE.

There is a limited representation of the cement industry in long-term energy models. Disaggregating the non-metallic minerals sector and modeling the physical demand instead of directly modeling the energy demand will allow the inclusion of bottom-up information on production technologies and regional energy efficiency and material efficiency potentials.

For the cement industry, important parameters that affect the energy development are the current regional energy and CO_2 intensities, adoption rates of energy efficiency technologies, energy efficiency and material intensity. Besides the guide for modelling the cement sector, presented in the appendix, in this paper, we propose two modeling approaches for cement for improvement of these processes in long-term energy models: 1) retrofitting with energy efficient technologies and 2) reducing the clinker to cement ratio. Based on this a number of key conclusions can be drawn.

There is a significant potential for energy savings from retrofitting. Cement plants that were built a number of years or even decades ago and that are still in operation are not as efficient as newly built cement plants. In addition, the level of energy efficiency and the production technologies used for cement production differ between regions. For the existing plants, retrofitting with energy efficient technologies/measures can offer significant energy savings, already in the short term, that cannot be neglected. Bottom-up details on the regional average energy intensity and on production technologies used along with information on energy efficiency options can be used by energy models to identify the potential for energy savings from retrofitting.

There is a significant potential for energy savings from increased clinker substitution. The effectiveness of implementing this strongly depends on the activity in other sectors and the scenario in question. Relating the clinker content in cement to the development of the steel industry and the electric power industry can have a significant impact on projecting energy use in the cement sector. For example, in a scenario where less coal-fired power plants are built or steel demand weakens, the availability on SCMs will decrease the potential for GHG abatement in the cement industry through clinker substitution. These results confirm the crucial role of connections between industries and show that GHG abatement measures in one industry can indirectly impact another. In such a case, to achieve even higher clinker substitution rates.

In addition, these results highlight that the production/generation of high and consistent quality SCMs and their effective utilization in processes such as cement making where they have the potential to significantly lower GHG emissions is of crucial importance especially in times/scenarios of low SCM availability.

Both measures can offer significant energy savings in the short term. Both retrofitting and the reduction of the clinker to cement ratio can offer significant energy and GHG savings already in the short term. These are not highly innovative measures surrounded by high uncertainties but well-known measures with tangible energy and GHG savings potentials.

Acknowledgement

The research leading to these results has received funding from the European Union Seventh Framework Programme FP7/2007-2013 under grant agreement n° 308329 (ADVANCE) and Global Environmental Research Fund” (2-1402) of the Ministry of the Environment of Japan.

Appendix 5A Energy Efficiency Measures/Technologies for Clinker Production

Table 5-10 Energy efficiency measures for clinker making – dry process cement plants (Worrell et al., 2013)

Energy Efficiency Measure	Specific Fuel Savings (GJ/tonne clinker)[1]	Specific Electricity Savings (kWh/tonne clinker)[1]	Investment Cost ($/tonne clinker)[1]	Estimated Payback Period (years)[1]
Clinker Making Process				
Energy Management and Control Systems	0.1-0.2	0-4.9	0.2-0.3	<2
Kiln Combustion System Improvements	0.1-0.4	-	1.00	1.0-5.0 (1)
Mineralized Clinker	0.0-0.2	0- -1.0	N/A	N/A
Indirect Firing	0.2	0- -0.6	6.7-9.3	>10 (1)
Oxygen Enrichment	0.0-0.2	(-)9- (-)32	3.5-6.9	N/A(1)
Mixing Air Technology (PH kilns)	0.20	(-) 0.03	1.2	2 (1)
Seal Replacement	0.02	-		<1
Kiln Shell Heat Loss Reduction	0.1-0.6	-	0.3	<1
Preheater Shell Heat Loss Reduction	0.02	-	0.3	6
Refractories	0.06	-	0.7	4
Conversion to Grate Cooler	0.3	(-)3.00- (-)6.00	10-14	>18
Optimize Grate Cooler	0.05-0.16	0.0- (-)2.0	0.7-2.1	2.00-7.00
Low-Pressure Drop Suspension Preheaters	-	0.6-4.4	3-4	>10 (1)
Heat Recovery for Power Generation	-	20.0	2.2-10.4	2.00-14.00 (1)
Conversion of Long Dry to Preheater	0.7-1.6	-	40.0	10 (1)
Increase Preheater Stages (from 5 to 6)	0.1	-	2-5	>7 (1)
Addition of Precalciner or Upgrade	0.2-0.7	-	15.0	>10 (1)
Conversion of Long Dry Kiln to Preheater Precalciner	0.84-1.11	-	30.0	>10 (1)

[1] The estimated energy and expenditure savings and payback periods are averages for indication, based on the average performance of the U.S. cement industry (e.g. clinker to cement ratio). The actual savings and payback period may vary by project based on the specific conditions in the individual plant.

Table 5-11 Estimated implementation rates of the different energy efficiency technologies in year 2010

Energy Efficiency Measures for Clinker Production	Europe	Africa	Asia & Oceania (excl. China. India	Brazil	Central America	China	CIS	Middle East	North America	South America (excl. Brazil)	India
Energy Management and Control Systems	20%	50%	25%	30%	20%	20%	10%	20%	20%	30%	15%
Kiln Combustion System Improvements	5%	50%	10%	40%	30%	20%	10%	20%	30%	35%	15%
Mineralized Clinker	5%	10%	10%	10%	10%	5%	5%	10%	10%	10%	2%
Indirect Firing	5%	10%	10%	10%	10%	5%	5%	10%	10%	10%	2%
Oxygen Enrichment	5%	10%	10%	10%	10%	5%	5%	10%	10%	10%	2%
Mixing Air Technology (PH kilns)	5%	10%	10%	10%	10%	5%	5%	10%	10%	10%	2%
Seal Replacement	25%	30%	25%	30%	25%	25%	10%	25%	25%	25%	10%
Kiln Shell Heat Loss Reduction	5%	40%	20%	40%	35%	20%	10%	25%	30%	40%	5%
Preheater Shell Heat Loss Reduction	5%	40%	35%	40%	35%	35%	10%	25%	35%	35%	10%
Refractories	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Conversion to Grate Cooler	20%	30%	20%	30%	20%	20%	20%	20%	20%	20%	12%
Upgrade clinker cooler	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	12%
Optimize Grate Cooler	30%	70%	80%	70%	80%	35%	80%	80%	80%	80%	12%
Low-Pressure Drop Suspension Preheaters	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%
Heat Recovery for Power Generation	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%	25%
Conversion of Long Dry to Preheater	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Increase Preheater Stages (from 5 to6)	10%	30%	20%	30%	20%	20%	20%	20%	20%	20%	10%
Addition of Precalciner or Upgrade	29%	11%	9%	0%	31%	0%	4%	12%	18%	33%	0%
Conversion of Long Dry Kiln to Preheater Precalciner	10%	2%	0%	0%	0%	0%	4%	0%	12%	0%	0%
Conversion from Wet to Dry precalciner Kiln	6%	4%	0%	0%	0%	10%	58%	0%	9%	0%	0%
Conversion from Semi-Wet Semi to Dry precalciner Kiln	8%	0%	0%	0%	0%	0%	3%	0%	0%	0%	0%

Appendix 5B Basic Guidelines for Modeling the Cement Industry

Energy demand

There are three main energy consuming processes in cement manufacturing: raw material preparation, clinker production (limestone calcination) and cement grinding. Energy is consumed throughout cement manufacture and can be broken down into: (i) electricity use for raw material preparation; ii) fuel and electricity use in clinker calcination; (iii) electricity use for clinker grinding; and (iv) fuel use for drying raw materials and additives (e.g. slag powder) (see Equation 5-10). Table 5-12 shows all variable definitions used in the equations. The most energy intensive step is the calcination of clinker, responsible for the majority of fuel use (Worrell et al., 2013).

$$E_{total,t} = E_{raw\ material\ pre.,t} + E_{fuel,kiln,t} + E_{el.,kiln,t} + E_{cement\ grinding,t} + E_{additives\ drying,t} \tag{Eq. 5-10}$$

Table 5-12 Variable definitions

Variable	Definition	Unit
I	i=1, 2 refers to the type of kilns used: 1) dry and 2) wet	None
J	j refers to the different types of fuels used	None
$Kiln_{ratio,i,t}$	The share of clinker produced with kiln type i in year t	%
$SEC_{thermal,i,t}$	Thermal energy use of kiln type i in year t	GJ/tonne clinker
$SEC_{elec,i,t}$	Electricity use of kiln type i in year t. It includes the electricity use for fuel preparation, and the electricity for operating the kiln, fans and coolers	GJ/tonne clinker
$SEC_{total\ el.,t}$	Electricity use for cement making in year t	GJ/tonne cement
$E_{total,t}$	Total energy use in cement manufacture in year t	PJ
$E_{cement\ grinding,t}$	Total electricity use for cement grinding in year t	PJ
$E_{raw\ material\ prep.,t}$	Total electricity use for raw material preparation in year t	PJ
$E_{additives\ drying,t}$	Total energy use for additives drying in year t	PJ
$E_{fuel,kiln,t}$	Total fuel use in cement kilns in year t	PJ
$E_{el.,kiln,t}$	Total electricity use in cement kilns in year t	PJ
$Q_{cement,t}$	Total cement output in year t	Mtonnes cement
$Q_{clinker,t}$	Total clinker output in year t	Mtonnes clinker
$CO_{2,total,t}$	Total CO_2 emissions from cement production in year t	Mtonnes CO_2
$CO_{2\text{-}fuel,t}$	Total CO_2 emissions from fuel combustion in year t	Mtonnes CO_2
$CO_{2\text{-}process,t}$	Total CO_2 emissions inherited to the clinker calcination process in year t	Mtonnes CO_2
$CO_{2\text{-}el.,t}$	Total CO_2 emissions from electricity generation in year t	Mtonnes CO_2
$Fuel_{ratio,j,t}$	Fuel share of fuel j in year t	%
$CEF_{fuel,j}$	CO_2 emission factor of fuel j	$kgCO_2/GJ$
$SEC_{thermal,t}$	Thermal energy use for clinker calcination in year t	MJ/tonne
$CEF_{el.,t}$	CO_2 emission factor for electricity generation in year t	$kgCO_2/GJ$
$Clinker_{ratio,t}$	The clinker to cement ratio in year t	%

Due to the limited regional information, not all variables in Eq. 5-10 can be defined/determined for every world region. In the following paragraphs we show how the total energy use ($E_{total,t}$), fuel ($SEC_{thermal,t}$) and electricity ($SEC_{total\ el.,t}$) can be calculated on a regional basis based on available information. Since information on regional electricity use per process step (i.e. raw material preparation, clinker burning and cement and additive grinding) is not available, we show an approach to determine the total electricity use in cement plants.

Fuel use

Most of the energy consumed in a cement plant is in the form of fuel that is used to fire the kiln. A mixture of mainly limestone, silicon oxides, aluminium oxides and iron oxides are burned in a kiln to produce clinker. Based on the moisture content of the raw materials, clinker production can take place in a wet, dry, semi-dry or semi-wet kiln. The dry process is the most energy efficient as the evaporation needs are low. The Commonwealth of Independent States (CIS) has a high share of the wet process (85%), while other regions that employ this technology are Europe (6%), China (10%) and the North America (9%) (see Table 5-3). Countries with a high share of the wet process will have a higher average fuel use in clinker making. Table 5-13 shows the typical energy intensities of the different kiln technologies.

Below we show two simple approaches that could be used by energy models for the construction of their base year energy use: 1) by using regional information readily available on the level of energy use per tonne of clinker or 2) by taking into account information on the production technology used in each region and the typical energy intensities of each technology.

Approach 1

The thermal energy use for clinker production ranges between 3.1 and 5.0 GJ/tonne clinker between the major world regions (see Figure 5-1). It differs mainly due to the kiln technology type used and the level of energy efficiency. The lowest energy consumption is observed in India where cement capacity increased significantly in recent years. The highest is in CIS which still relies heavily on the wet process.

Approach 2

The fuel requirements for clinker making could also be estimated based on the information available on the type of technologies used (e.g. wet, dry, semi-dry) in the different regions (see Table 5-3), the typical energy intensities of these technologies (Table 5-13), and the amount of clinker produced in each region (see Equation 5-11). Statistics on clinker production are not available. However, clinker production can be estimated by multiplying the reported cement production with the clinker to cement ratio of that region (see Figure 5-6). Clinker can be substituted by industrial by-products such as coal fly ash, blast furnace slag or pozzolanic materials (e.g. volcanic material). The relative importance of additive use can be expressed by the clinker to cement ratio.

$$E_{fuel,kiln,t} = \left(\sum_i Kiln_{ratio,i,t} \times SEC_{thermal,i,t}\right) \times Q_{clinker,t} \quad (5\text{-}11)$$

Table 5-13 Fuel use by type of kiln technology

Kiln technology	JRC-IPTS, 2010 (GJ/tonne clinker)	U.S. EPA, 2007 (GJ/tonne clinker)	Weighted average (GJ/tonne clinker) (WBCSD, 2009)
Dry with preheater and precalciner	3.0-4.0	2.9-3.8	3.3
Dry with preheater (without precalciner)[1]	3.1-4.2	4.4	3.7
Long dry (without preheater and precalciner)	up to 5.0	5.2	4.5
Semi-wet, semi-dry	3.3-5.4[2]	-	3.8
Wet	5.0-6.4	5.7-10.2 (6.0 typical)	6.3

[1] The energy use differs with the number of preheater stages: 3.4-3.8 GJ/tonne for 3 preheater stages; 3.2-3.6 GJ/tonne for 4 preheater stages; 3.1-3.5 GJ/tonne for 5 preheater stages; 3.0-3.4 GJ/tonne for 6 preheater stages (ECRA, 2009)

[2] The energy use for raw material drying is not included.

Approach 2 leads to slightly different results from the fuel use appearing in Approach 1. For most of the regions, Europe, Africa, Central America, CIS, Middle East, Asia & Oceania, North America and South America when using approach 2 and the average energy intensity of the technologies shown in Table 5-13, the estimated fuel use is close (± 0.15 GJ/tonne clinker) to the fuel use shown in approach 1. For China, India, and Brazil, the result in approach 2 is a higher fuel use (0.4-0.5 GJ/tonne) than approach 1. New efficient capacities built in these regions have decreased the overall energy use and this could be corrected in approach 2 by using lower typical energy intensities than the ones appearing in Table 5-13.

Total electricity use (electricity use for raw material preparation, kiln operation, cement and additives grinding) accounts for about 20% of the overall energy needs in a cement plant and ranges between 90 and 150 kWh/tonne cement (IPTS/EC, 2010). Electricity is primarily used for raw material, fuel, and cement grinding. The typical power consumption breakdown in a cement plant using the dry process is as follows (ECRA, 2009):

- 5% raw material extraction and blending,
- 24% raw material grinding,
- 6% raw material homogenization,
- 22% clinker production and fuel grinding,
    - 38% cement grinding, and
    - 5% conveying, packaging, and loading.

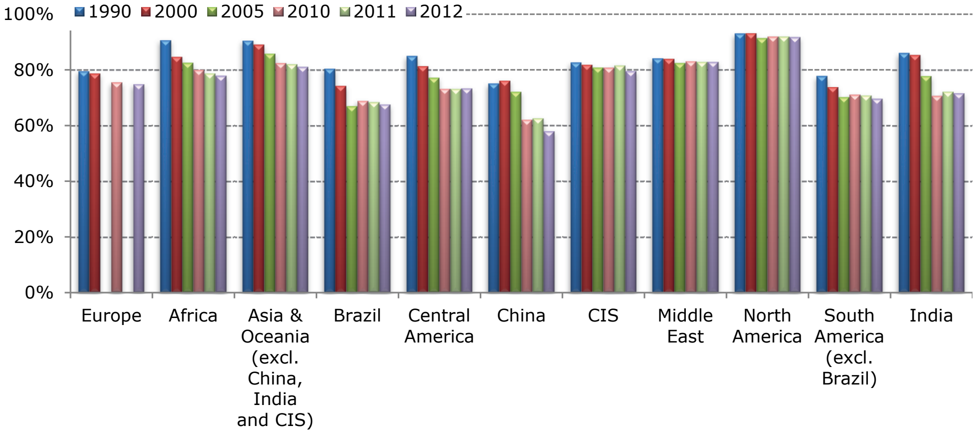

Figure 5-6 Clinker to cement ratios per region (WBCSD, 2014; Xu et al., 2012; Zhang et al., 2015)

Energy models could develop their base year energy use based on the information that is available on the regional total electricity use per tonne of cement (approach 1) or based on the type of technologies used and the typical energy intensities (approach 2). The lack of information on the regional installed capacity of grinding technologies will limit the usability of approach 2 by the models. However, the approach is presented below as models could use the information to determine regional electricity use for clinker burning only. In addition, we present the typical electricity intensities of the different grinding technologies.

Approach 1

According to the WBSCD database, in 2012, the total electricity use ranged between 81 and 126 kWh/tonne cement. The lowest electricity use is observed in India and the highest in the North America and CIS (see Figure 5-7).

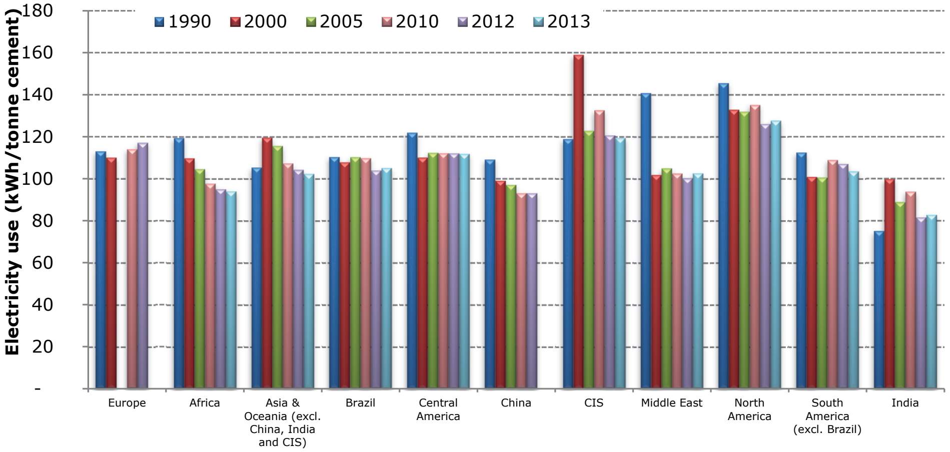

Figure 5-7 Average electricity consumption for cement making per region (WBCSD, 2014; Xu et al., 2012)

Approach 2

The electricity use in kilns can be estimated based on the typical energy intensities of the different kiln types and the type kilns used in each region (see Table 5-14). About 22% of the electricity consumed is used for clinker making and fuel grinding. Plants using the wet process consume about 32 kWh/tonne clinker for fuel preparation and for operating the kiln, fans and the coolers while plants operating the dry process consume about 36 kWh/tonne clinker (Worrell et al., 2013). The electricity use for clinker making in a specific region can be estimated from Eq. 5-12.

$$E_{el.,kiln,t} = \left(\sum_i Kiln_{ratio,i,t} \times SEC_{elec,i,t}\right) \times Q_{clinker,t} \qquad \text{(Eq. 5-12)}$$

More than 60% of the electricity consumed is used for grinding. Electricity use is influenced by the grinding technology employed, material properties and product fineness. Plants employing high pressure roller presses and roller mills are less electricity intensive than plants using ball mills. Currently, about 70% of installed mills in grinding plants are ball mills. In newer plants this share is lower, estimated at 50% as more energy efficient mills types are used (Harder, 2010).

Although there is information available on the typical energy intensities of the various grinding technologies (see Table 5-14), information on the share of the different grinding technologies per world region is scarce. Therefore, it is not possible to estimate the regional electricity use, based on this data alone. Approach 2 can only be used to estimate electricity use for clinker making.

Table 5-14 Electricity use for raw material and cement grinding (Worrell et al., 2013)

Grinding technology	Raw material grinding (kWh/tonne raw material)[1]	Cement grinding (kWh/tonne cement)[1]	Fuel grinding (kWh/tonne coal)[1]
Ball mill	19-29	32-37	
Horizontal roller mill	7-8	18-21	
Vertical roller mill	<10	21-23	15-23
Roller presses	15	19-21	
Impact mill			50-66
Tube mill			28-29

[1] The actual electricity use will heavily depend on the material properties and required fineness.

Total energy use

The total energy consumption of cement making in different world regions can be estimated by Eq. 5-13. As the available data on the electricity use involve the total electricity use, in the equation below, $E_{raw\ material\ prep.,t}$, $E_{el.,kiln,t}$, and $E_{cement\ grinding,t}$ from Eq. 5-10 are aggregated into $SEC_{total\ el.,t}$.

$$E_{total,t} = \left(\sum_i Kiln_{ratio,i,t} \times SEC_{thermal,i,t}\right) \times Q_{clinker,t} + SEC_{total\ el.,t} \times Q_{cement,t} \quad \text{(Eq. 5-13)}$$

A simple way to project energy use under a baseline scenario would be to assume that energy efficiency in cement manufacture improves annually by a certain rate. This improvement could be the result of an autonomous energy efficiency improvement and a policy induced energy efficiency improvement. The historical energy use trends for the cement industry indicate that in the past years, fuel use in clinker production and electricity use for cement production (total electricity use) experienced an annual decrease of 0.9% and 0.5%, respectively (Kermeli et al., 2014).

CO_2 emissions

Most of the CO_2 emissions in cement making are released during clinker calcination. Approximately 62% of the CO_2 emissions are process related while the remaining 38% is released during fuel combustion (IPTS/EC, 2010). The CO_2 emissions inherent to the process amount to 0.5262 kg per kg of clinker produced (IPTS/EC, 2010). The CO_2 emissions from fuel combustion depend on the energy intensity of the kiln system and the carbon intensity of the fuel used. To calculate the total amount of CO_2 released in the atmosphere, the CO_2 emissions from electricity generation also need to be added.

$$CO_{2,total,t} = CO_{2-fuel,t} + CO_{2-process,t} + CO_{2-el.,t} = \sum_j \left(Fuel_{ratio,j,t} \times CEF_{fuel,j} \times SEC_{thermal,t}\right) \times Q_{clinker,t} + \sum_i \left(CEF_{el.,t} \times SEC_{el.,t}\right) \times Q_{cement,t} + 0.5262 \times Clinker_{ratio,t} \times Q_{cement,t} \quad \text{(Eq. 5-14)}$$

Figure 5-8 shows the different types of fuels used in the cement industry. In Europe, around 45% is comprised by alternative fuels such as a variety of wastes such as tires, waste oil, plastics and solvents and biomass.

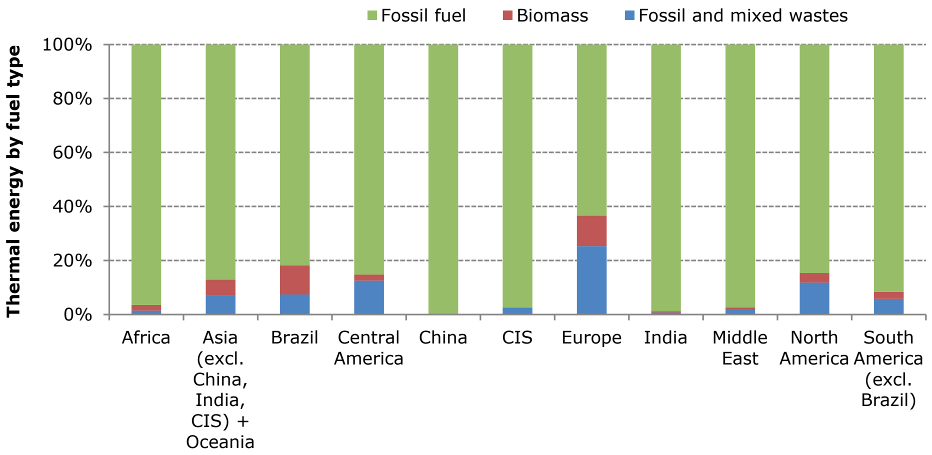

Figure 5-8 Thermal energy use for clinker making by fuel type (WBCSD, 2014).

Appendix 5C SCM availability and utilization in 2050

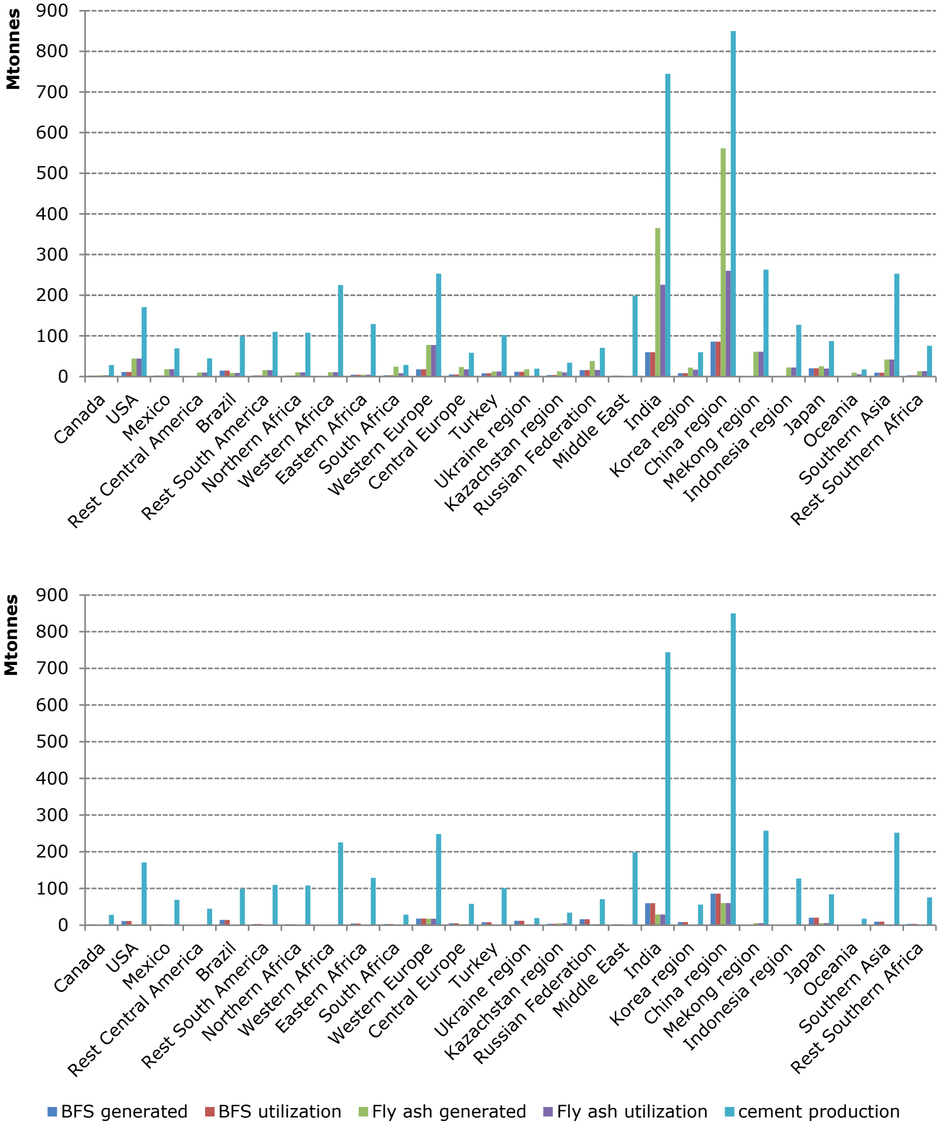

Figure 5-9 SCM availability and utilization under the a) baseline improved and b) mitigation improved scenarios in 2050

Appendix 5D Clinker to cement ratios in 26 regions

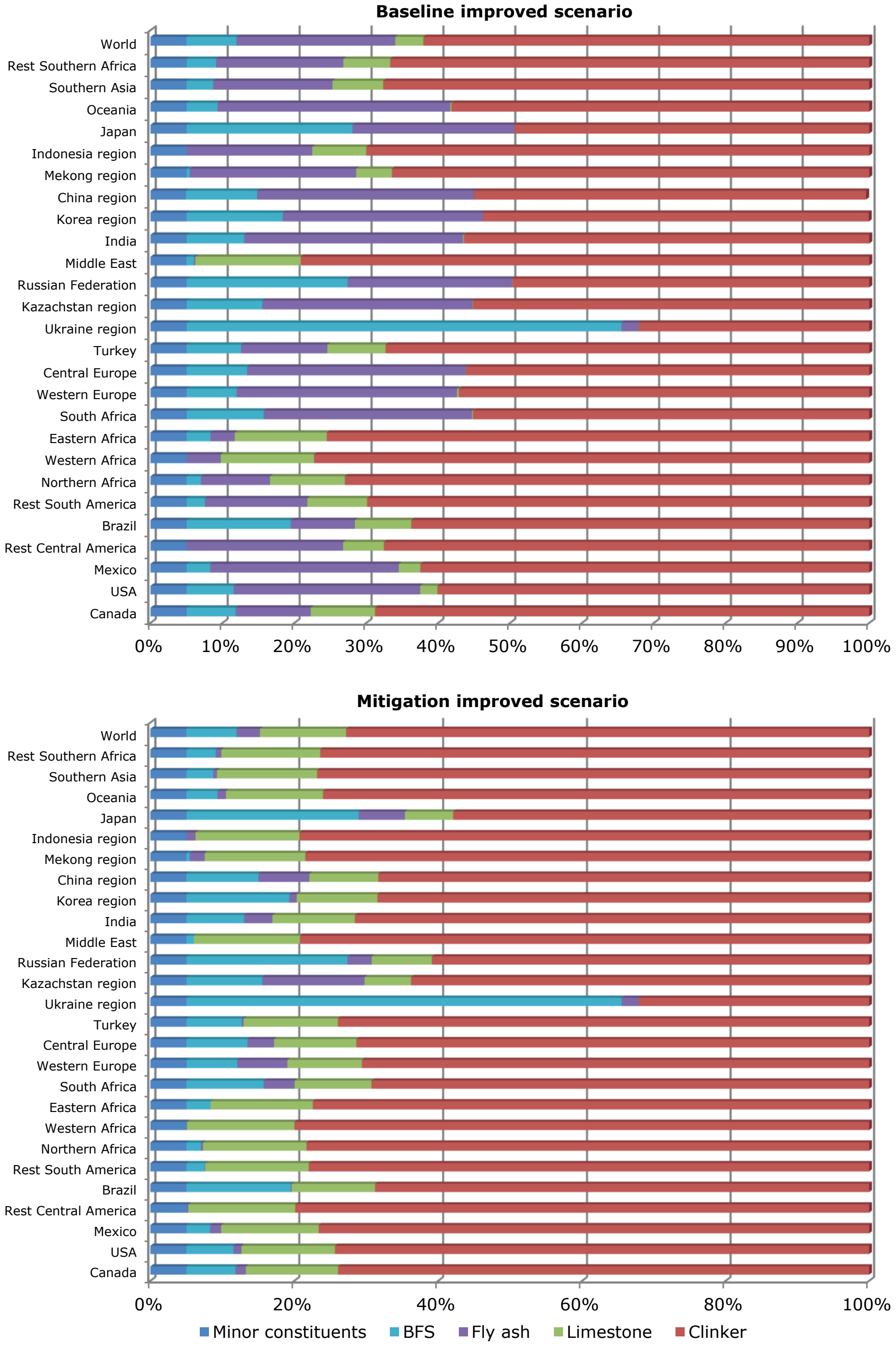

Figure 5-10 Cement composition in 2050 in the a) baseline and the b) mitigation improved scenarios.

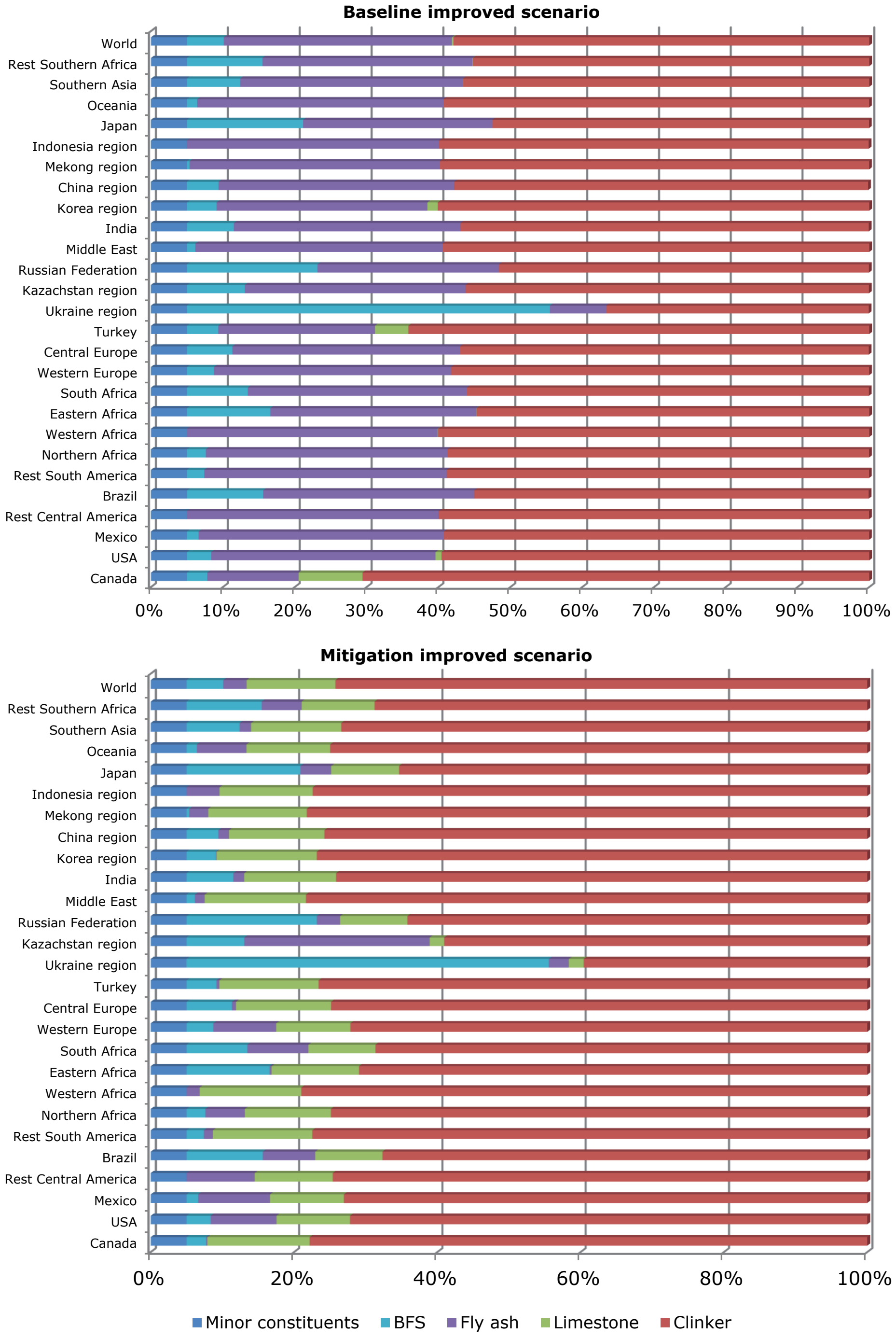

Figure 5-11 Cement composition in 2100 in the a) baseline and b) mitigation improved scenarios.

6 Improving material projections in IAMs: the use of a stock-based versus a flow-based approach for the iron and steel industry[49]

Abstract

The steel industry is responsible for a large share of the industrial energy consumption and GHG emissions and several long-term energy models have some representation of this sub-sector. We find that models, commonly use a flow-based approach for projecting steel demand neglecting that in-use steel stocks serve as a better demand indicator than steel consumption. We then develop a stock-based method that uses the historical steel stock results from detailed Material Flow Analysis (MFA) for steel demand projections and implement this in the IMAGE Integrated Assessment Model (IAM).

Large differences between the two approaches arise. For the first half of the 21st century, global steel demand increases with both approaches and at a similar rate to reach 2,300 Mtonnes/yr by 2050. For the second half of the 21st century, however, the developments differ drastically. With the stock-based approach, global steel demand decreases by 0.8%/a to reach 1,600 Mtonnes/yr, while with the flow-based approach it increases by 0.3%/a to reach 2,600 Mtonnes/yr in 2100. Given that steel production levels have a profound contribution to GHG emissions, using the right approach is crucial. This means that long-term energy models may currently overestimate the industrial emissions in the last half of the century.

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[49] Based on Kermeli, K., O.Y. Edelenbosch, W. Crijns-Graus, B.J. van Ruijven, D.P. van Vuuren, and E. Worrell. Improving material projections in IAMs: the use of a stock-based versus a flow-based approach for the iron and steel industry. Submitted for publication to the journal Energy.

6.1 Introduction

In 2017, global steel production exceeded 1,600 Mtonnes; that is more than double the amount of steel produced in 1980 (Worldsteel, 2018). The increased steel demand resulted in increased energy consumption and Greenhouse Gas (GHG) emissions. In 2017, total energy use for steel making (incl. energy use in coke ovens and blast furnaces) reached 33 EJ (21% of global industrial energy use) ranking it as the second largest energy using industrial sub-sector (IEA, 2018). Iron and steel production is expected to increase in the future in order to meet the increasing demand for steel, especially in the developing countries. Incremental changes in current steel production processes with the adoption of currently available technologies would not be enough to meet the emission goals (Fleiter et al., 2019), with innovative technologies (e.g. hydrogen-based, switch to electrified processes) having to be widely adopted to decarbonize this industry.

Following the industry's important role in energy consumption (IEA, 2018), some Integrated Assessment Models (IAMs) represented iron and steel as a separate industrial sector. IAMs are used to generate global or regional scenarios on energy use, GHG emissions, climate and other issues by combining knowledge from different disciplines and they are widely used in climate change assessments (e.g. in (IPCC, 2014; GEA, 2012; OECD, 2012; UNEP, 2002). For the energy system, IAMs describe both energy demand and supply systems. Traditionally, IAMs had much more detail in terms of energy supply than energy demand, given the difficulties in describing the heterogenous activities and technologies associated with demand. Over time, however, most IAMs have started to include more demand detail. Still, there are large differences in the way these models deal with energy demand, which also leads to diverging model results (Edelenbosch et al., 2017). Determining the right level of detail in energy demand represents an important dilemma for the global and long-term IAMs: while on the one hand, including demand-side details increases policy-relevance and possibly the representation of relevant sub-sector dynamics, on the other hand, IAMs also need to simplify the systems they represent for reasons of transparency and uncertainty.

In this article, we discuss the representation of steel-demand projections in IAMs and the options for improvement. Understanding and capturing the drivers of material demand and its saturation level is of crucial importance for long-term projections used in the evaluation of scenarios for achieving climate goals (Watari et al., 2020), as it affects all GHG mitigation scenarios that need to be evaluated. Ideally, total demand would be coupled to steel demand for construction, automotive and machinery sectors in both developing and industrialized countries. It is argued (Müller et al., 2007; Pauliuk et al., 2013a) that in-use steel stocks (i.e. the steel contained in products that are in-use in a given year) instead of annual steel flows can better indicate the services that steel provides in an economy and therefore would be a better predictor of future steel demand. Increasing population, industrialization and urbanization are currently the main drivers of steel demand and when the growth in these drivers comes to a halt, steel consumption drops (Müller et al., 2011).

There are two main advantages of such a stock-based approach. The first is that such an approach considers the demand for services that steel-containing products offer. This would allow modelling material demand more realistically through reduced demand for services, or through substitution of materials or function. This would make IAMs more relevant in assessing circular economy policies and strategies (Aguilar-Hernandez et al., 2021). The second is that with such an approach, also using the age distribution of the in-use steel stock, the amount of retired steel can be calculated, which can be used to produce steel from post-consumer scrap. This allows for more accurate forecasting of the different routes (each with distinctively different energy use) for steel production and results in improved modeling of the total energy use and GHG emissions.

The flow approach is currently the more common approach used in IAMs to model steel demand, where steel consumption is directly correlated with income levels (van Vuuren et al., 1999; de Vries et al., 2001; Crompton, 2000; Hidalgo et al., 2005; Neelis and Patel, 2006; Corsten, 2009; Zhou et al., 2013; van Ruijven et al., 2016. These relationships can be derived from the historical correlation of per capita Gross Domestic Product (GDP) with steel use intensity (defined as steel consumption in kg per GDP). These two variables are typically assumed to be related to each other through an inverted U-shaped curve, where steel use intensity becomes decoupled from GDP per capita growth at higher values (Vuuren, 1999). Alternatively, an S-shaped curve is used to relate steel consumption per capita and GDP (Ayres, 1987; Gielen and van Driel, 1997; Akashi et al., 2011; van Ruijven, 2016). As a third alternative, mostly for the short-term, extrapolations of past growth rates can be used for projections (Wang et al., 2007; Pardo and Moya, 2013).

There are several studies that analyze current and possible future developments of accumulated in-use steel stocks. Using a top down approach, steel stocks were estimated for Japan (Hirato et al., 2009) and for a Chinese province (Lou and Shi, 2008). Material Flow Analysis (MFA) was used to estimate the steel stock build-up and scrap availability in the Chinese residential sector (Hu et al., 2010). An MFA analysis was also used to estimate steel stocks in the EU27 from 1945 to 2013 (Panasiyk et al., 2016) and to estimate steel stocks in 200 countries for the period 1700-2008 (Pauliuk et al., 2013a). Scenario analyses were performed for the future iron in-use stocks in China (Yue et al., 2016), with the future steel demand in China based on the analysis of future product stocks (floor space, vehicles, household appliances etc.) (Yin and Chen, 2013), using both material flow dynamics and market dynamics (e.g., resource prices, capacity planning) to estimate future Chinese steel demand (Wang et al., 2014; Wang et al., 2017). Using the same concept, “stocks drive flows” (Müller et al., 2006), future steel stocks and steel demand were estimated for 42 countries (Hatayama et al., 2010), for China (Pauliuk et al., 2012) and for ten world regions (Pauliuk et al., 2013b) up to 2100. The studies suggest that in-use steel stocks in all economies will saturate after they reach a certain level, and this will have an impact on the demand for new steel.

However, the practical application of a stock-based steel demand modeling approach is limited in IAMs, the main reason being the lack of stock data. With IAM projections continuing to rely on steel flows, the importance of material cycles is overlooked, with the links between economic activities and material use (the true driver of material demand) and recycling potentials not accurately captured (Pauliuk et al., 2017). Linking industrial ecology studies, devoted in analyzing material cycles, to IAMs, could thereby be the way to more robust evaluation of model scenarios (Pauliuk et al., 2017) without substantially increasing the complexity (e.g. gathering and linking trade, production and manufacture data) of IAMs.

In this study, we investigate the IAM state of the art modelling and examine how a steel stock approach can be applied to an IAM model and whether this will affect the projected sector development. For this, we use the data from (Pauliuk et al., 2013a) to estimate the future steel stock build-up that is used in the IMAGE integrated assessment model to estimate future steel consumption. Because the IMAGE model already has a detailed flow-based steel module (van Ruijven, 2016), we compare the steel consumption that these two approaches yield. In so doing, we essentially compare a method based on the saturation of per capita consumption to a method based on the saturation of per capita stocks while using the same GDP and population drivers to better understand how the different methodological approaches impact the projected development of the steel sector.

This article is structured as follows. In Section 6.2, we give an overview of how steel demand or the energy consumption for steel making and the scrap availability are modeled in several IAMs. In Section 6.3 we present the method we used for projecting steel consumption based on the stock analysis in the IMAGE model, in Section 6.4 we compare the different modeling results and in Section 6.5 we shortly address the impact on energy projections. Finally, in Sections 6.6 we discuss the results and in Section 6.7 we draw the main conclusions.

6.2 Overview of iron/steel sector representation in IAMs

Energy system models vary in the way they represent the industrial sector. A detailed Table in Appendix 6A gives an overview on how leading energy models[50] account for two important parameters in steel modeling 1) steel demand/consumption and 2) steel recycling/scrap availability.

Out of the twelve models, seven have a representation of the iron and steel industry (POLES, WEM, ETSAP-TIAM, IMAGE, AIM-CGE, DNE21+ and GCAM). In the rest, the iron and steel sector is part of a more aggregate cluster; in MESSAGE it is part of the whole industry, in GEM-E3 part of the ferrous metals industry, in REMIND part of a so-called stationary sector that also includes the residential and commercial sectors, in WITCH part of the non-electric sector that also includes transportation and residential sectors, and in Imaclim-R part of the energy-intensive industrial sector.

Physical steel demand is accounted for in all models that have an explicit iron and steel industry representation except for AIM-CGE and GCAM. In AIM-CGE the demand is represented in monetary units and in GCAM steel demand is indirectly accounted for as a part of a single category of homogeneous industrial good. In POLES, ETSAP-TIAM, IMAGE and DNE21+ the steel demand is mostly coupled to the per capita economic activity. This is commonly done by a relationship between steel intensity (annual steel consumption per capita) and economic activity (GDP per capita) based on historical data. Based on this relationship, future annual demand trajectories/developments and saturation levels are determined for each region. In

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[50] Selected from the EU ADVANCE project, described at http://www.fp7-advance.eu

WEM, although additional parameters are considered, such as industry value added and end-use energy prices, it is unclear from available documentation what their exact role is. The models without an explicit representation of the steel industry relate industrial energy demand directly to economic growth.

Steel recycling is considered by three models: IMAGE, WEM and DNE21+. In IMAGE, the use of steel production processes that use scrap as an input is limited by the availability of steel scrap and product quality requirements. A scrap model identifies all the steel flows in an economy and all sources of scrap (circulating, prompt and obsolete) (Patel, 2006). Although the steel stock built-up is assessed, it is not used as an indicator of steel services, and thereby not used to determine the steel demand. In WEM, a material flow model is used to assist estimations on the level of material efficiency and future steel demand and scrap availability (semi-manufacturing, manufacturing and post-consumer scrap) projections (OECD/IEA, 2016) built upon other research on steels stocks. The material flow analysis in WEM, has a dual purpose: 1) to estimate scrap availability, and 2) to help estimate future steel demand. In DNE 21+, the share of the secondary route (using primarily steel scrap as input) is set to range between fixed minimum and maximum limits based on exogenously determined scrap availability.

Although not a part of ETSAP-TIAM, a scrap availability model (SAAM) is used in combination with the ETSAP-TIAM model to estimate future steel demand, with scrap availability based on the residence time of steel products in the various activity sectors and steel production technology choices (Morfeldt et al., 2013). One of the steel demand scenarios developed reflects assumptions on the per capita in-use steel stock saturation levels per activity sector from an MFA (Pauliuk et al., 2013a).

6.3 A steel-stock based consumption model

In this section, we present a method for projecting steel demand based on the insights from stock analysis. In Section 6.3.1, we first discuss an approach for projecting steel stocks based on available historical steel stock data. In Section 6.3.2, we discuss how the steel stocks that retire annually can be projected based on residence times, and finally in Section 6.3.3, we indicate how future steel demand can be projected.

6.3.1 Method for projecting steel stocks

To estimate future steel stocks for the 26 regions used in the IMAGE model we performed a two-step regression analysis, first for all OECD countries and then for all 26 IMAGE regions. The first regression analysis has been solely performed to identify the function that better describes steel stock developments. The steps followed are:

1) Regress historical per capita steel stocks (dependent variable) against country income levels (expressed in GDP/capita) (independent variable) using data from all OECD countries for the period 1900 to 2008.

To describe stock developments, a variety of functions have been used in literature, either relating material stocks to time (Toi and Sato, 1998) (Pauliuk et al., 2013b) or to GDP/capita (Hatayama et al., 2010). Given that economic growth and the development of steel sector are closely related, and that economic growth is a commonly used model driver, the former approach was adopted. The per country and per sub-sector steel stock data were taken from (Pauliuk et al., 2013a), and the population[51] and income data[52] (in real GDP/capita) from (Clio-Infra, 2018). We evaluated several function types in SPSS, namely linearized function and non-linear S-shaped functions. The best fit was found (based on the std. deviation) with the S-shaped function:

$$S_t(t) = \frac{S_{sat}}{1 + e^{\left(a - b * \frac{GDP(t)}{capita}\right)}} \qquad (6\text{-}1)$$

where S_t is the per capita steel stock in year *t*, S_{sat} is the per capita saturation level of in-use steel stocks (limit of growth) and *a* and *b* are constants to be defined in the regression with the constant *b* specifying the width or the steepness of the curve. At low incomes there is an exponential growth of steel stocks until a certain income is reached. After that, the growth is restricted until it reaches the upper asymptote. Hence, the total curve describes a typical sigmoid or S-shaped curve.

Figure 6-1 shows the historical per capita in-use stocks and GDP for the four activity sectors in OECD countries. The black dotted line shows the results when the regression is performed with the data from all OECD countries together (total OECD). Table 6-1 reports the R^2 and the

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[51] For the period 1900-1960 the population data are reported in 10-year intervals. The data for the intermediate years were estimated with the use of polynomial interpolation (spline interpolation).

[52] Although in this analysis the use of GDPppp values would be preferable, GDP real values were used instead due to the poor data availability prior to 1970.

standard deviation values (RMSE) for the regressions for the total OECD data. Table 6-2 shows the range in the saturation levels resulting from the separate regression for each OECD country.

Table 6-1 S-shaped regression model results for the total OECD country data for the period 1900-2008

Activity sector	Transportation	Construction	Machinery	Others	Total
$\mathbf{S_{sat}}$ (tonnes/capita)	2.52	8.75	1.35	0.66	12.28
a	2.64	2.73	2.66	2.79	2.61
b	0.000221	0.000221	0.000375	0.000344	0.000252
R^2	0.61	0.66	0.58	0.66	0.75
Std. deviation (RMSE)	0.49	1.69	0.39	0.16	2.1

Table 6-2 Steel stock saturation levels and income levels identified with the regression analysis for the OECD countries

	Range saturation level (tonnes/capita)	Average Income level (GDP/capita)
Transportation	0.9-2.5	~19,000
Construction	5.6-12	~20,000
Machinery	0.5-2.4	~13,000
Others	0.4-0.9	~14,000

Although there is a strong correlation between GDP and material demand, with the relationship between GDP and the demand for materials (and stocks) being bi-directional[53] (Haberl et al., 2020), to stay close to the approach used by energy models we have made the simplification that GDP drives the stocks and not vice-versa.

2) Aggregate the historical country and sectoral data on steel stocks from (Pauliuk et al., 2013a) to the 26 regions used in the IMAGE model; and

3) Perform a second regression analysis by using the S-shaped curve (Eq. 6-1) for all 26 regions and for all activity sectors (transportation, machinery, construction and others).

Future GDP/capita projections were taken from the ssp scenario baseline scenario in IMAGE (van Vuuren, 2017) which are based on Dellink et al. (2017). For some developing regions, with economies at early stages of development, and a very low in-use steel stock accumulation, the regression analysis using Eq. (6-1) is not able to yield meaningful results (e.g. very high or very low Ssat, that is not comparable to the saturation levels identified for OECD countries and shown in Table 6-2). To solve this, we run the second regression analysis, for these regions, with the constraint that the Ssat should be between the ranges in Table 6-2.

The data regressed in step 1) include only mature economies because their economic structure has changed a lot during the different stages of economic development. Thereby, identifying the relationship between the per capita in-use steel stock and GDP during the different stages of OECD countries' maturing is possible, as opposed to the countries with economies in the

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[53] i.e. GDP being a driver for material consumption but also the opposite, material consumption being a driver for GDP.

first stages of development. However, the main assumption here is that when such a relationship is used in step 3), all developing countries that are currently low in accumulated steel stocks, will follow the same historical trends.

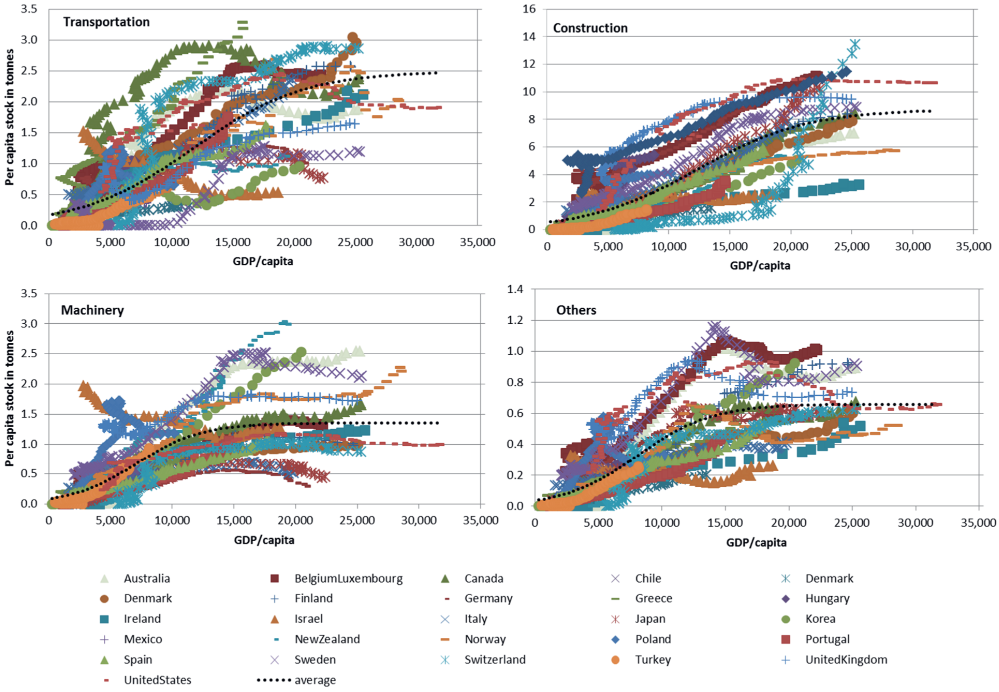

Figure 6-1 Per capita historical in-use steel stocks in OECD countries a) transportation, b) machinery, c) construction, and d) others (constructed based on modelled steel stock (Pauliuk et al., 2013a)).

6.3.2 Method for projecting retired steel

Little reliable information is available on steel product lifetimes (Müller et al., 2007). In general, steel used in construction takes the longest to retire (35-100 years) with buildings retiring sooner than other structures such as bridges, airports and harbors. Next is steel used in transportation (6-35 years), with passenger cars typically retiring sooner than buses, trucks, trains, aircrafts and ships. The machineries and the other activity sectors encompass heterogenous mixes of goods. Average lifetimes for machines range between 5 and 37 years, with ICT-related machinery having an average lifetime of 5-8 years and machines used in industrial manufacturing typically lasting more than 10 and up to 37 years. Other appliances such as household appliances and packaging have a shorter lifetime (5-14 years), although their lifetime was longer in the 1990's (Rincon-Aznar et al., 2017).

To estimate the annual retirement rate *f(x)* we use the historical retired steel volumes on a country level from (Pauliuk et al., 2013a), aggregate them to the 26 regions used in IMAGE and fit them to the sigmoid curve, Eq. (6-2):

$$f(x) = \frac{1}{1+e^{-k(x-x_o)}} \qquad (6\text{-}2)$$

where x_o is the mid-point of the sigmoid. It represents the year at which 50% of the steel consumption in year 1 is retired (equal to the average lifetime shown in Table 6-3) and the constant k is the logistic growth rate or steepness of the curve.

The analysis results in different retirement rates and average product lifetimes for each sector for all 26 regions. Based on how fast steel is retired, three distinct groups were observed, “Long lifetime”, “Medium lifetime”, and “Short lifetime”, and all countries are assigned into one of these groups. Table 6-3 shows for each group (“Long”, “Medium”, and “Short”) and sector, the parameters of Eq. (6-2). Appendix 6C presents the group to which each region is assigned for all four activity sectors and presents evidence from the literature of product lifetime deviations between regions.

The curves in Figure 6-2 show the rates at which steel is retired per group and sector up to 2100. For example, in the case of the transportation sector, and for the group “Short lifetime”, if in year *t* 10 Mtonnes enter the in-use steel stocks, in year *t+5* about 3.5% of the steel will retire (0.35 Mt), in year *t+10* about 11% of the steel will retire (1.1 Mt), and so on. It will take 20 years for practically all steel from that age-cohort to retire. This is represented by the integral (the area below the curve).

Although it is important to capture the past retirement patterns to estimate current levels of concentrated in-use steel stocks, it is uncertain whether these patterns will continue. Steel stock lifetime is a critical parameter in the dynamic relationship between retired steel stock and steel consumption. We therefore perform a sensitivity analysis and estimate retired steel and annual consumption for five scenarios:

i) “Static Lifetime”: All regions stay in their assigned group for ever (see Appendix 6C);

ii) “Converging Lifetime”: All regions move to the global average lifetime of the specific sector (the results of the global regression analysis per sector for this scenario are shown in Figure 6-3 and Table 6-2);
iii) “Long Lifetime”: All regions move to the Long lifetime group;

iv) “Medium Lifetime”: All regions move to the Medium lifetime group;

v) “Short Lifetime”: All regions move to the Short lifetime group.

Table 6-3 Eq. (6-2) parameters from the regression analysis

		Long lifetime	Medium lifetime	Short lifetime	Average lifetime (used in the convergence scenario)
Transportation	x_o	26	20	10	19
	k	0.206	0.250	0.444	0.164
	R^2	0.99	0.99	0.96	0.77
	Std. deviation	0.03	0.03	0.06	0.19
Construction	x_o	94	50	38	71
	k	0.054	0.113	0.149	0.047
	R^2	0.85	-	-	0.49
	Std. deviation	0.07	0.1	0.1	0.26
Machinery	x_o	39	30	16	31
	k	0.130	0.187	0.291	0.111
	R^2	0.98	-	0.97	0.81
	Std. deviation	0.20	0.1	0.17	0.18
Others	x_o	20	15	8	15
	k	0.298	0.377	0.510	0.237
	R^2	0.93	-	0.89	0.73
	Std. deviation	0.30	0.1	0.40	0.21

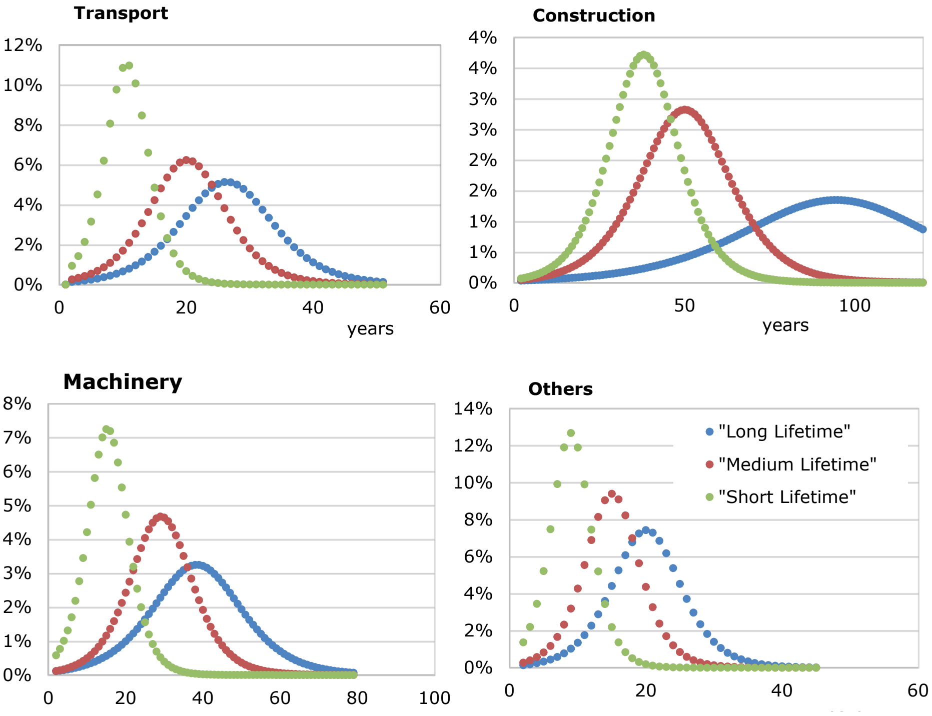

Figure 6-2 Fraction of retired steel (y-axis) in the years after consumption in the fours activity sectors (percent of steel retired per year)

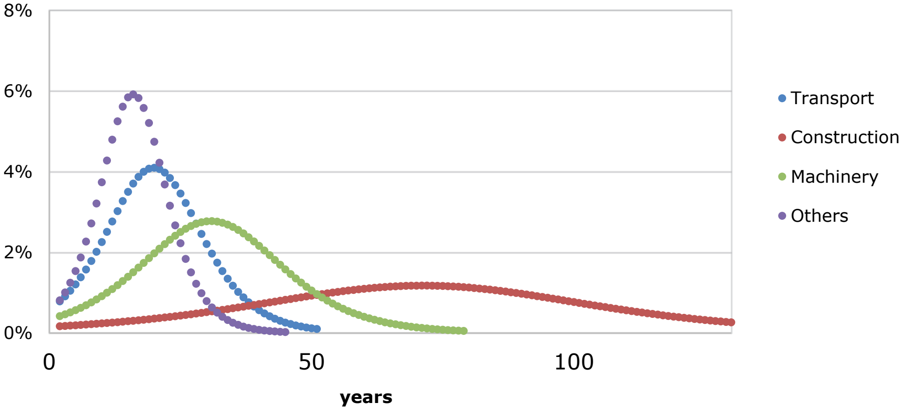

Figure 6-3 Fraction of retired steel in the years after consumption (y-axis) for the four activity sectors (“Converging Lifetimes”)

6.3.3 Method for projecting future steel demand

To satisfy the increasing in-use steel stock levels and to replace the steel stock that reached the end of its lifetime and will be retired, “new” steel will need to be added each year (see Figure 6-4).

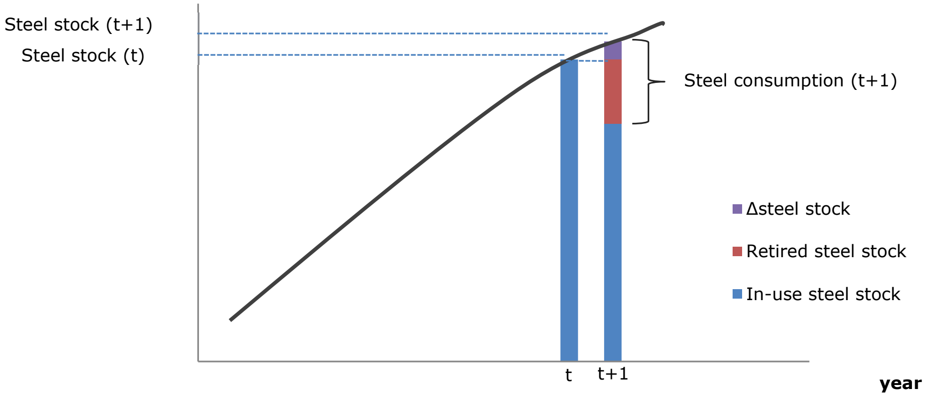

Figure 6-4 Steel consumption as a result of steel stock change and retired stock

The future annual steel consumption can thereby be calculated by adding the difference in steel stock levels (ΔSteel stocks) between the year t and the year t+1 plus the amount of steel that is retired in year t+1, see Eq. (6-3) (Müller, 2006), and Figure 6-4:

$$Annual\ Steel\ Consumption(t+1) = Steel\ Stock(t+1) - Steel\ Stock(t) + Retired\ Steel(t+1) \qquad (6\text{-}3)$$

The steel stock in year t is calculated from Eq. (6-1) and the retired steel stock from Eq. (6-2). The steel stock in year t-1 is known.

With this formulation, steel inputs and outputs from building renovations are not considered. Nevertheless, these amounts should be limited as primarily wood, concrete and plastics are used/discarded from repair and maintenance activities in buildings (Gielen, 1997).

6.4 Steel projections

6.4.1 Steel stock projections

Figure 6-5 shows the estimated future accumulation of total steel stocks in the different regions. Total in-use steel stocks were calculated from Eq. (6-1) that estimates the future per capita steel stocks multiplied with the future population.

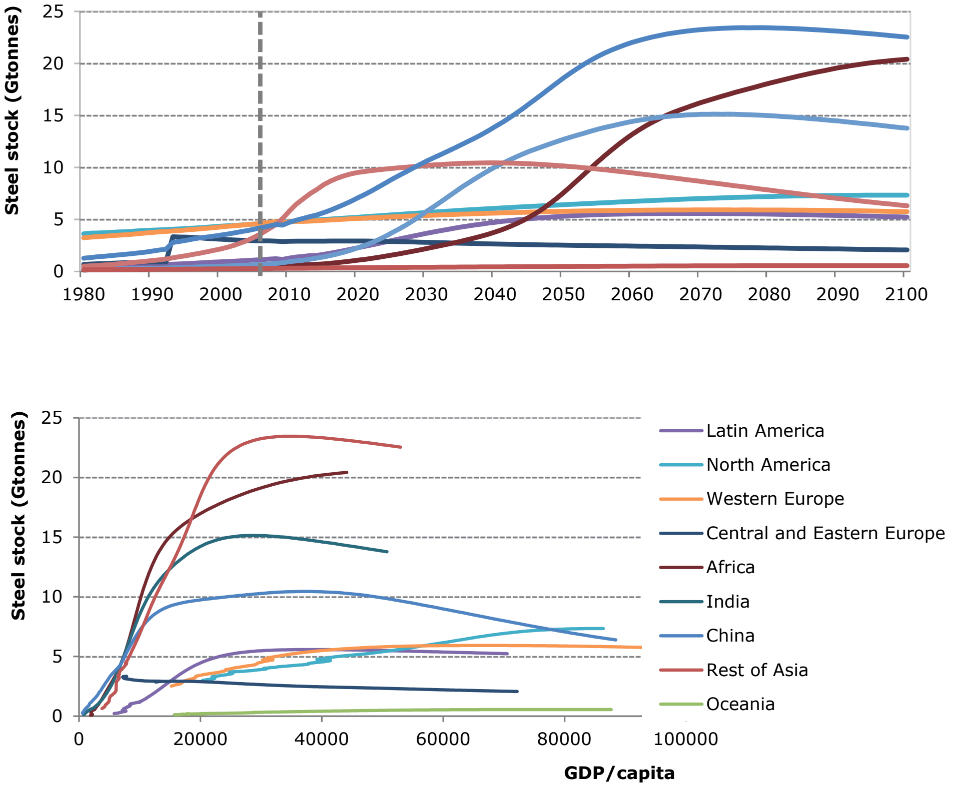

Figure 6-5 Total steel stock projections in the main world regions a) top graph as a function of time (the vertical dotted line distinguishes the projections (right) and the empirical data (left)) and b) bottom graph as a function of income levels

Rest of Asia and Africa have the highest steel stock build-up followed by India. These results show that steel stocks in China will continue only to slightly increase until 2040 to peak at 10.5 Gtonnes and will then start decreasing. The peak in steel stocks is estimated to be reached earlier in China than in India. Steel stocks in India are estimated to peak at around 15 Gtonnes in 2070. In Africa steels stocks are projected to start increasing after 2030 and not reach their peak point by the end of the century. In the North America and Western Europe, the situation is different as steel stocks are found to only experience slight growth and have basically reached a plateau.

For many regions it is observed that total stock saturation starts at income levels of more than $20,000 per capita. As the per capita in-use steel stocks saturate at high income levels, any decline seen in Figure 6-5

Figure **6-5** (bottom) is solely attributed to population decline. The income level at which the saturation starts depends on the shares and developments of the individual sectors. Appendix 6D shows projected steel stocks on a more detailed regional level (26 regions).

Figure 6-6 shows when the total per capita stock saturation level (Ssat) is reached for 26 regions. The regions for which the regression analysis yielded high Ssat levels (>10 tonnes/capita) are the United States, Western Europe, Rest of South Asia, Middle East, Korea, Japan, Canada, and Oceania.

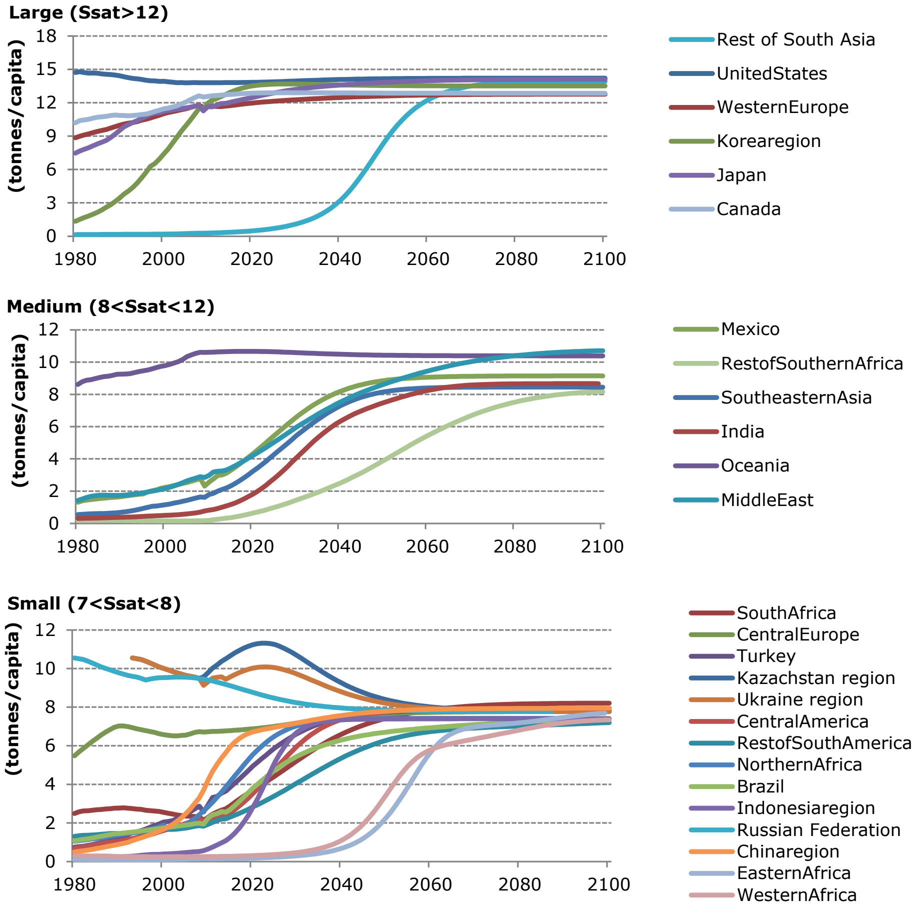

Figure 6-6 Total per capita steel stocks (in tonnes/capita); a) regions with large Ssat, b) regions with

medium Ssat and c) regions with small Ssat.

Overall, the total per capita stocks are shown to saturate between 7.2 and 14.2 tonnes per capita. Appendix 6B shows the Ssat levels per region and per activity sector as well as the *a* and *b* parameters[54]. Although per capita steel stock in China (Figure 6-6) was experiencing a stronger annual increase in the past years, after 2020 the increase is shown to slow down to saturate at 7.9 tonnes/capita in 2056. This, along with the growing population, explains why total steel stocks are found to increase up to 2040 in China.

As it is assumed that per capita steel stocks remain the same after the saturation level is reached, the only reason total steel stocks decrease after 2040 is due to decreases in population. Results for India are similar, with the only difference that the total per capita steel stock saturates later in time. In India the per capita total steel stocks saturates at 8.7 tonnes.

6.4.2 Retired steel stock projections

Every year, a share of the in-use steel products reaches the end of their lifetime and is decommissioned. Figure 6-7 shows the retired steel stocks per activity sector for the two scenarios on lifetime developments i) “Static Lifetime” and ii) “Converging Lifetime”.

In the years to come, the volumes of retired steel are estimated to greatly increase from about 500 Mtonnes in 2008 to 1,600 Mtonnes and 1,700 Mtonnes in 2100 in the “Static” and in the “Converging Lifetime” scenarios, respectively. In 2008 and in the “Static Lifetime” scenario, most of the retired steel came from the transport (180 Mtonnes/yr) and the construction sectors (170 Mtonnes/yr), followed the machinery (94 Mtonnes/yr) and the others (91 Mtonnes) sectors. In the “Converging Lifetime” scenario the retired steel volumes are very similar, only in the construction sector they appear to be lower (130 Mtonnes/yr).

In the construction sector, where differences are more pronounced, the average lifetime used in the “Converging Lifetime” scenario is 71 years, which is 25 years more than the average lifetime used in the “Static Lifetime” scenario for Central and Eastern Europe, thereby leading to lower retired steel findings. Similarly, for China, India, and Africa, the “Converging Lifetime” scenario (71-year average lifetime) finds lower volumes of retired steel than the “Static Lifetime” scenario (100-year average lifetime).

Essentially, large volumes of retired steel in a specific year reveal the years for which consumption was high in the past. For example, in India, steel stock retirement in the transport sector is found to peak between 140 and 160 Mtonnes in 2085. This is because steel consumption in the sector peaked 28 and 20 years prior in the “Static Lifetime” and “Converging Lifetime” scenarios, respectively.

Total steel stocks retired in 2050 or 2100 are estimated to be much higher than in 2008. This will impact the future demand for steel, as to replace the retired steel stock, “new” steel needs to be consumed for the total steel stock to remain on the same level. This dynamic might not be

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[54] For a few regions with very low in-use steel stocks (at the beginning of the S-shaped curve) the regression analysis yielded unrealistic results, for example very high Ssat. For these regions, we assumed that the development would be the same with a similar/close region.

as significant today (low volumes of retired steel and increasing per capita steel stocks), but it can very well be in the future (high volumes of retired steel and saturating per capita steel stocks)

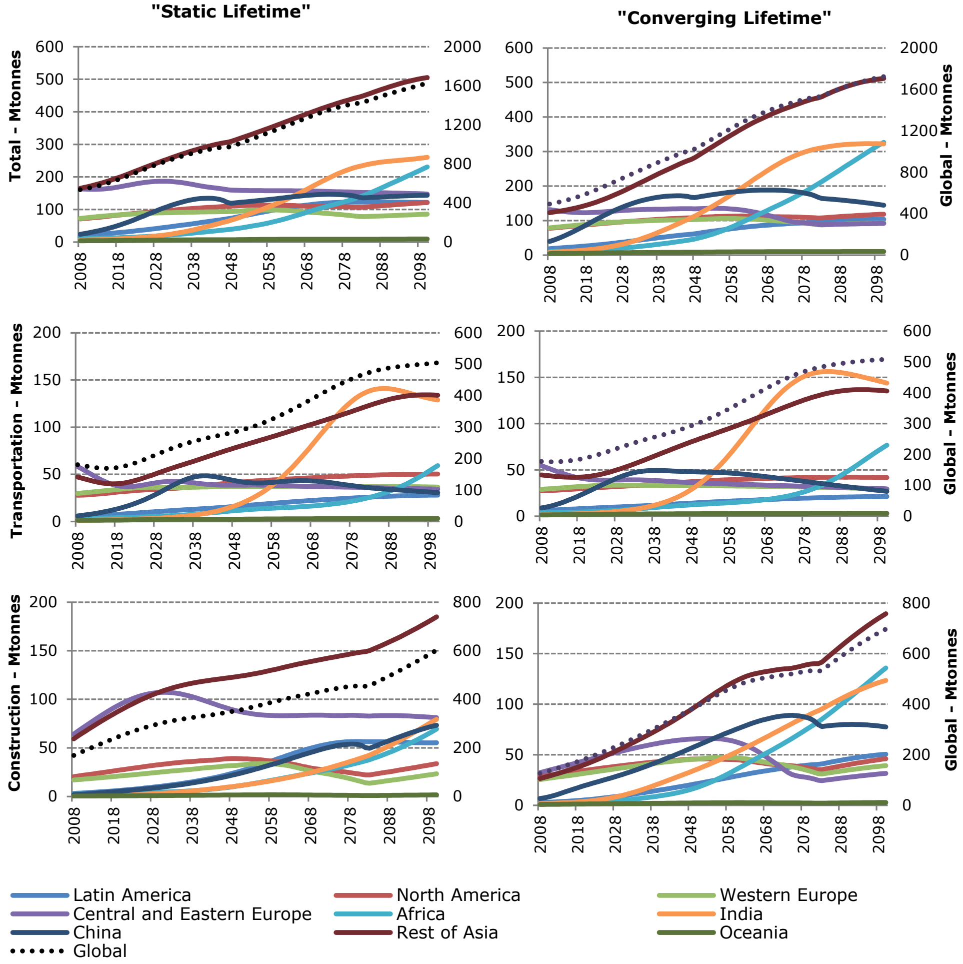

Figure 6-7 Total annual volumes of retired steel stocks (in Mtonnes) per region and per activity

6.4.3 Steel consumption projections

In the original flow-based approach used in IMAGE and other IAMs, countries/regions with a low income will have a low per capita steel consumption. As the incomes rise, per capita consumption will rise until a certain per capita steel consumption and income level reached (determined based on analysis of historical trends). At high incomes, and as the economy becomes less material intensive, the steel consumption will decouple from GDP. In the steel stock-based approach, steel consumption is not linked to GDP/capita but steel stocks are, and they are assumed to saturate when a certain level of GDP is reached.

Figure 6-8 shows the global steel stock and steel consumption projections with the use of the stock-based approach (under the “Static Lifetime” and “Converging Lifetime” scenarios) and the flow-based approach (“original”) in IMAGE. The stock-based approach leads to an increasing consumption in the first half of the century, as in the original flow-based approach, but in the second half of the century a decline is forecasted as in many regions stocks will saturate. With the flow-based approach, global steel consumption is estimated to continue its increasing trend in the second half of the century, although it slows down, reaching 2,700 Mtonnes/yr in 2100. This is 75% higher compared to the “Converging Lifetime” scenario in the stock-based approach, where steel consumption reaches 1,500 Mtonnes/yr in 2100.

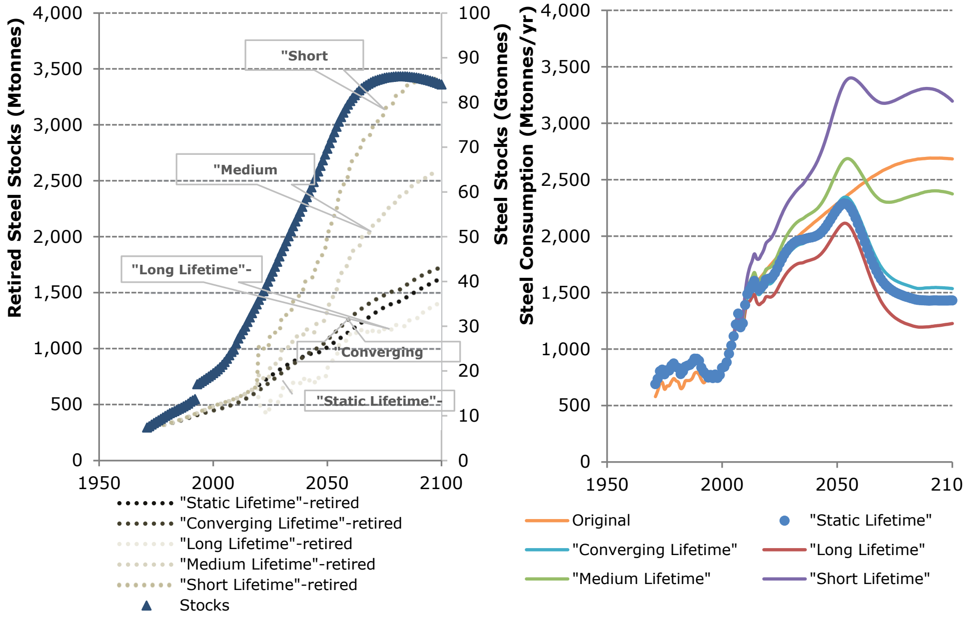

Figure 6-8 Projections with the flow-based and stock-based approach a) global steel stocks and retired steel and b) steel consumption in IMAGE

The steel consumption calculation in the stock-based approach is a two-fold function depending on i) the change in required steel stocks and ii) on the amount of retired steel (see Eq. 6-3). When steel stocks saturate (see Figure 6-8), the annual demand is only driven by the retired steel, thus leading to a low consumption level through Eq. 6-3. This obviously also depends on the volumes of retired steel stocks. Figure 6-8 shows that before 2050, steel is largely consumed to satisfy the increasing steel stocks, while after 2050 steel is consumed to replace retired steel stocks. This makes steel demand projections very sensitive to the assigned lifetimes, especially for the second half of the century, when large stocks have been accumulated.

To understand the impact the lifetime has on steel consumption projections, we also show in Figure 6-8 steel consumption under the scenarios “Long Lifetime”, “Medium Lifetime” and “Short Lifetime”. When steel products are used longer (“Long Lifetime”) steel consumption is lower than in the “Converging Lifetime” scenario, reaching 185 Mtonnes/yr in 2100, and when steel products are retired early (“Medium Lifetime”) and very early (“Short Lifetime”), steel consumption is significantly higher, reaching 364 Mtonnes/yr and 536 Mtonnes/yr in 2100, respectively. The difference between the “Converging Lifetime” and “Medium Lifetime” scenarios can be attributed to the different lifetimes for construction. In “Medium Lifetime” the steel used in construction has a lifetime of 50 years and in “Converging Lifetime” 71 years. Between these two scenarios all other average lifetimes are almost the same (see Table 6-3).

A drop in steel demand when the stock-based approach is used, is especially pronounced for China, Rest of Asia, India, Africa, and Latin America (see Figure 6-9). In China, steel consumption is estimated to decrease at an annual rate of 12% between 2013 and 2024 (“Converging Lifetime” scenario) instead of 0.1% with the flow-based approach. In scenario “Short Lifetime” steel consumption after 2030 is substantially high but still a pronounced decrease is found before 2030 as a result of stock saturation.

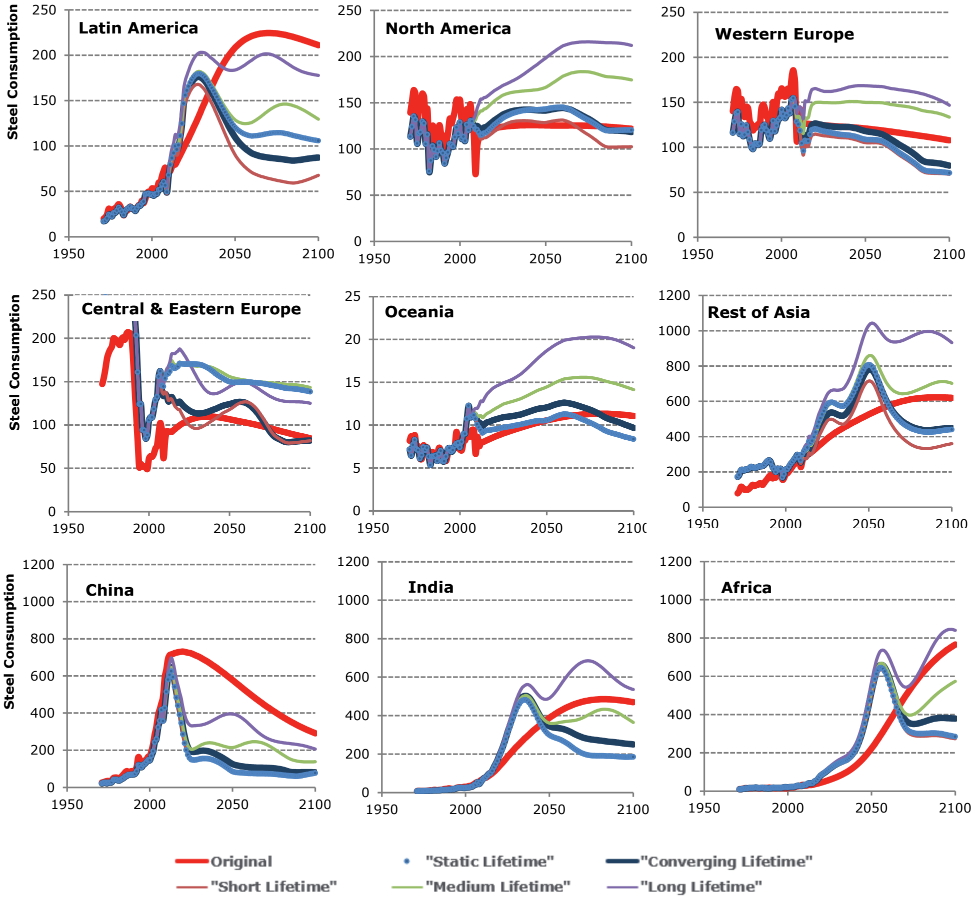

Figure 6-9 Regional steel consumption scenarios under different lifetime scenarios (unit: Mtonnes/yr)

Steel consumption in India is estimated with the stock-based approach to peak at 505 Mtonnes/yr in 2036 (“Converging Lifetime”), while with the flow-based approach steel consumption climbs to 485 Mtonnes/yr in 2085. India is a country that is projected to not have reached its per capita steel stock saturation point yet. The per capita steel stock logistic growth function results in higher consumption between 2010 and 2040, than in later years. Similar are the cases in China where consumption peaks between 2010 and 2020, and Africa where consumption peaks between 2050 and 2060 and then experiences a very rapid decrease.

Western Europe, a region that has already reached its steel stock saturation point according to the regression analysis, shows a different pattern. Here, annual consumption is estimated to remain constant and is mainly driven by the retirement of steel.

In the scenarios “Medium Lifetime” and “Short Lifetime”, consumption is found to experience a second peak later in China, Africa, India, Rest of Asia. This means that steel consumed at earlier years of strong steel stock growth is being replaced by new steel at the end of its lifetime. However, this would mean that steel products have a very short lifetime (e.g., 10 years for transport, 38 years for construction).

Overall, global steel consumption between the flow-based and the stock-based approaches shows similar growth in the 2008-2050 period, estimated to reach about 2,300 Mtonnes/yr in 2050 (see Figure 6-8) increasing at an annual rate of 1.3% and 1.6%, respectively. Nevertheless, different regions are responsible for this growth [China (25%), Rest of Asia (23%), India (17%) and Africa (10%) with the flow-based, and Rest of Asia (34%), Africa (23%), India (15%) and China (6%) with the stock-based approach]. With the flow-based approach, China is estimated to experience de-growth after 2020. However, the decoupling from GDP is slow in China, while the Rest of Asia catches up. In the stock-based approach (“Converging Lifetime” scenario), demand in China is estimated to drop rapidly. This is because: i) steel stock growth slows down and ii) retired steel is not substantial as existing stocks are not that old (steel stock build-up 2009-2020). In the stock-based approach, after a certain level of stock/capita is reached, absolute steel stocks stop growing unless population grows. Rest of Asia and Africa are estimated to reach peak demand around 2050, which is higher than the demand estimated in the flow-based approach. Projections for Western Europe, North America, Central and Eastern Europe and Oceania provide similar results for both approaches.

In the second half of the century, the projected global steel consumption varies strongly between the two approaches. The flow-based approach sees a continuing increase in demand that reaches a plateau after 2080 (2,700 Mtonnes/yr in 2100) while on the other hand, the stock-based approach, sees a decreasing trend (1,500 Mtonnes/yr in 2100). Demand dominating regions are quite similar [Rest of Asia (23%), Africa (29%), India (17%) and China (11%) in the flow-based and Rest of Asia (29%), Africa (25%), India (15%) and China (5%)]. The lower consumption estimates with the stock-based approach are because peak demand is reached earlier in all developing regions while the decrease is more pronounced.

6.5 Impact on the energy use forecasts

This study was limited to projecting steel consumption based on a stock-based method for use in IAMs. In this section, we show the impact that the method adopted has on energy consumption projections in the IMAGE model.

Scrap availability is an important parameter in energy use projections. The IMAGE model has a scrap model that estimates future scrap availability based on a detailed MFA whereby future in-use steel stocks are estimated from typical steel product lifetimes and steel statistics (for more information see Neelis and Patel, 2006). For 2100, IMAGE finds the volumes of steel scrap available for use in steel making at around 1,600 Mtonnes/yr. This includes, obsolete, prompt and circulating scrap. In the "Converging Lifetime", retired steel (obsolete scrap) is found to reach 1,700 Mtonnes/yr in 2100. If 70% of the obsolete scrap is recovered, and another 70% of the scrap generated during manufacturing[55] is also recovered, the scrap available for use in steel making with the stock-based approach is around 1,300 Mtonnes/yr.

Assuming an energy use for 2100[56] of 18 GJ/tonne steel for steel manufacturing from iron ore in blast furnaces and basic oxygen furnaces (BF/BOFs), and 4.3 GJ/tonne steel for steel making from scrap with the use of electric arc furnaces (EAFs) (Worrell et al., 2007), we can estimate the 2100 energy consumption with both approaches[57]. Table 6-4 shows the steel scrap shares in total steel production and the energy consumption with both approaches. Due to the higher steel consumption projections with the flow-based model, the energy use is shown to be 51% higher when compared to the stock-based approach. This can solely be attributed to the higher steel demand projections found with the flow-based approach.

Table 6-4 Impact of steel demand projection methods on the energy consumption in 2100

	Stock-based approach	Flow-based approach (IMAGE model)
Apparent crude steel consumption (Mtonnes)[1]	1,670	2,685
Scrap availability (Mtonnes)	1,294	1,598
Steel scrap to production ratio	77%	60%
Energy consumption in EAFs (PJ)	5,563	6,871
Energy consumption in BF/BOFs (PJ)	7,513	19,564
Total energy consumption (PJ)	13,077	26,435

[1] The stock-based approach calculates the annual consumption of finished steel products while the flow-based approach in IMAGE calculates the annual crude steel consumption. According to Worldsteel (2019), on a global level, the consumption of finished steel products is about 8% lower than consumption of crude steel.

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[55] We assume that the scrap recovery rates are at 70%, same as in IMAGE (Neelis and Patel, 2006).

[56] We assume that no innovative processes are implemented, and the energy use is equal to energy use in the Best Practice Technologies (BPTs).

[57] This is just an estimate based on the shares of the scrap availability. Models have many other assumptions/scenarios that can influence the final energy consumption (e.g. the share of the direct reduced iron production process, or the type of casting).

In a scenario in which the energy required to manufacture steel from iron ore fall to 12.5 GJ/tonne steel[58], the 2100 energy use with the flow-based approach would be 20.5 EJ and with the stock-based approach 10.3 PJ. The former is still 100% higher as the main energy demand driver is the production and not the energy intensity.

6.6 Discussion of uncertainties

There are multiple uncertainties. Key uncertainties are the assigned stock saturation levels in developing countries that are estimated from past steel stock developments in OECD countries. The estimated overall saturation levels in mature economies cover a relatively broad range (8-15 tonnes per capita). Insights behind the underlying reasons for differences in saturation levels could lead towards better approximation of the right saturation level of each developing region. This is especially true for regions where the regression analysis is not able to yield meaningful results. For these regions, the assumption was made that they will follow the same steel stock development as similar regions.

Uncertainties are also inherited from the historical steel stock estimates that are the result of MFA analysis. The MFA analysis is based on limited data with uncertainties related to the activity sector breakdown, and the lifetimes per activity and per country. Other uncertainties that can have a significant impact on the results are the iron content of traded goods, formation of obsolete stocks, and any misreporting of scrap and steel flows.

In the flow-based approach, steel consumption is apparent steel use (ASU) (obtained from the summation of steel production plus imports minus exports) (van Ruijven et al., 2016). In the stock-based approach, indirect steel trade is also considered; thus, steel consumption represents true steel use (TSU). ASU is higher than TSU for countries that indirectly export steel (e.g. Korea, China, Germany, Italy) and lower than TSU for countries that indirectly import steel (e.g. Canada, Russia, U.K). However, when aggregating into regions these differences become smaller. In 2017, global TSU was 6% lower than ASU (Worldsteel, 2019). In addition, the results when the stock-based approach is used are in finished steel product consumption while in IMAGE in crude steel consumption. On a global level, the steel use of finished steel products is about 8% lower than the crude steel consumption (Worldsteel, 2018).

Steel demand projections, especially for the second half of the century and after the peak on steel stocks, are mainly driven by the retired steel (i.e. stock replacement). Steel consumption is sensitive to the assigned lifetimes of the various steel-containing products. Product lifespans vary among countries and do not remain fixed with time. To add to the complexity, the average lifetime of each steel activity sector and for each region depends on the mix of the different assets, e.g. the share of trucks and ships in overall transportation, which also does not stay fixed with time.

For this reason, we estimate steel consumption under five scenarios with varying lifetimes. We consider the “Converging Lifetime” and the “Static Lifetime” scenarios to be more representative, both yielding similar regional results with global steel consumption decreasing

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[58] The energy use of producing steel in the DR RES with H2+EAF process is estimated at about 12.5 GJ/tonne (Keys et al., 2019).

after 2050. The “Converging Lifetime” scenario assumes that all regions converge to the global average lifetime of the steel activity sector and is very similar to the “Medium Lifetime” scenario (medium retirement rate) except for the construction sector. When the “Converging Lifetime” scenario is used, developing regions with a very long lifetime in transport (group “Long”: 30 years) will move towards a more typical for the developed regions average lifetime (group “Medium”: 20 years). Similarly, regions such as Korea and Japan with very short lifetimes (group “Short”: 10 years) due to the ongoing restructuring and development of strong economic growth, will move to a more typical average lifetime for the sector.

Scenarios “Long Lifetime” and “Short Lifetime” are considered to be extreme. However, they give an indication of steel demand developments when all regions use steel products efficiently (group “Long”) or inefficiently (group “Short”). Here, by efficient we mean no early decommissioning. Scenario “Long Lifetime” in this case could be representative of product lifetime extension in a circular economy. In 2100, steel consumption is estimated to reach 1,230 Mtonnes/yr in scenario “Long Lifetime”, and 3,200 Mtonnes/yr in scenario “Short Lifetime”, which is not so much more than the current annual consumption. The difference in demand between “Medium Lifetime” and the “Converging Lifetime” scenarios can be attributed to the lifetime used in the construction sector (“Medium”: 50 years, “Converging”: 71 years).

China is a region that, although assigned a long lifetime (group “Long”), literature suggests much shorter lifetimes than the average in the construction sector. Chinese steel demand is estimated at 81 Mtonnes/yr in scenario “Converging Lifetime” and at 140 Mtonnes/yr in scenario “Medium Lifetime”. Scenario “Medium Lifetime” in this case would be more representable for China if we assumed that reported lifetimes continue for the next 80 years while scenario “Converging Lifetime” if China would move to a more typical lifetime for the sector.

6.7 Conclusions

The way energy models can profit from the adoption of a stock-based approach is twofold: 1) steel stocks simply serve as a better driver of steel demand and 2) using a stock-based approach has different dynamics (can allow for better modelling of steel scrap availability, enable models to create circular economy scenarios etc.).

Currently, the main drawback is the lack of data. To overcome this, a better understanding of variations on steel stock saturation levels as well as on the retirement rates on a country level is needed.

The method presented in this paper allows for the simple incorporation of insights on historical steel stock developments and saturation levels gained from detailed MFAs in long-term energy models that commonly use a flow-based approach.

6.7.1 Main Conclusions

Based on the stock-based analysis and the comparison of steel consumption projections with the stock-based approach and the flow-based approach, the following main conclusions are drawn:

The build-up of steel stocks for most developing countries/regions is ongoing and is projected to peak in the coming decades and then gradually decrease. This is the result of increases in per capita steel stocks driven by higher income levels and population. A slowdown in global steel stock build up is estimated to begin after 2060 and peak by 2080 at 85 Gtonnes. China is projected to peak by 2040, India and Rest of Asia by 2070, and Africa is not projected to peak before 2100. Developed countries/regions have already accumulated the bulk of steel stocks, as per capita steel stocks experience saturation.

Global steel demand projections with the stock-based and the flow-based approach, are similar in the periods of growth but differ in the periods of decline. For the first half of the century (year 2008-2050), both approaches show a continuous increase in global steel consumption (albeit with differences between countries). Consumption experiences an annual growth of 1.6% and 1.3% with the stock-based and the flow-based approach, respectively. Only in the second half of the century global steel consumption projections would start to differ for the two approaches. With the stock-based approach, steel consumption will start decreasing after 2050, with an annual rate of 0.8% to reach 1,600 Mtonnes/yr by 2100. Small annual changes in total steel stocks that occur when stocks are no longer experiencing high growth (close to saturation) mean that steel consumption is primarily driven by stock retirement. With the currently implemented flow-based approach, steel consumption will continue to grow with an annual rate of 0.3% to reach 2,600 Mtonnes by 2100, and lead to about 75% higher annual steel demand compared to the stock-based approach. Given that steel production has a profound contribution to global greenhouse gas emissions, this means that IAMs may currently overestimate the industrial emissions in the last half of the century.

The volumes of retired steel are projected to substantially increase in the coming decades. As the high volumes of steel consumed in previous years will reach the end of their lifetimes they will need to be decommissioned. To replace retired steel stock, "new" steel needs to be consumed for the total steel services provided in an economy to remain on the same level. We found that about 1700 Mtonnes/yr of obsolete scrap will become available in 2100, equal to the steel demand in the same year (retired steel is the only driver of steel demand after stocks have saturated*)*. This could mean that future steel demand could be to a great extent satisfied by reusing obsolete scrap produced with the low energy intensive secondary steel making route.

The projected regions to dominate in global steel consumption vary between the stock- and flow-based approach. With the flow-based approach, in 2050 China will be the main steel consumer (25%), followed by Rest of Asia (23%), India (17%) and Africa (10%). With the stock-based approach Rest of Asia will dominate steel consumption (34%), followed by Africa (23%), India (15%) and China (6%) ("Converging Lifetime" scenario). Chinese demand decreases drastically as steel stocks saturate early and accumulated steel stocks are not mature enough to be decommissioned. In 2100, dominating regions are quite similar [Rest of Asia (23%), Africa (29%), India (17%) and China (11%) in the flow-based and Rest of Asia (29%), Africa (25%), India (15%) and China (5%)] with both approaches.

Following the stock-based approach, the model projects steel consumption in China and India, to peak at 625 and 484 Mtonnes/yr, respectively and then decrease drastically. With the stock-based approach steel consumption was projected to abruptly decrease at an annual rate of 12% in China and 3.3% in India within a 10-year period after the peak has been reached. This shows that decreasing GHG emissions may be hard when many developing regions are still building-up their stocks, but it may be easier later when stocks have saturated. For Western Europe and North America, future steel consumption was shown to remain constant. When the flow-based approach is used, steel consumption in developed economies is quite stable.

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Appendix 6A Detailed comparison of energy models

Table 6-5 Modeling steel demand and scrap availability in energy models.

Energy system models	Model concept/type	Industrial sector breakdown	Steel demand	Energy demand (if no physical demand is projected)	Recycling/Scrap availability
POLES - Prospective Outlook on Long-term Energy System	partial equilibrium with detailed sectoral energy demand[1]	**Iron and steel**, chemicals and petrochemicals, non-metallic minerals, others[3]	Inversed U-shaped relationship between economic activity and steel intensity. [21]	-	The share of secondary steel route depends on scrap availability. In-use steel stocks are evaluated to estimate scrap availability. [21]
WEM - World Energy Model	partial equilibrium with detailed sectoral and energy demand[19]	Aluminium, **iron and steel**, chemicals and petrochemicals, cement, pulp paper and printing, others[19]	Steel demand is based on insights from a material flow model of the steel industry (no clear description available)[19]	-	Scrap availability is determined with the use of a material flow model. Assumptions on material efficiency are based on insights from the material flow analysis. [19]
ETSAP-TIAM	linear programming partial equilibrium, with bottom-up details[20]	Pulp and paper, chemicals, **iron and steel**, non-ferrous metals, non-metals, other industries[20]	Inversed U-shaped relationship between economic activity and steel intensity[15]	-	Steel production is differentiated between secondary and primary based on production costs [3]
ETSAP-TIAM+SAAM (Scrap Availability Assessment Model)*	steel sector simulation model with explicit steel consumption representation	Iron and steel	Alignment of previous research indicating stock saturation levels of industrialized countries. Linearly decreasing growth rates stabilizing at a level of 12 tonnes of in-use steel stock per capita.[16]	-	Evaluation of scrap availability based on future demand scenarios and historic steel consumption. Insights on steel stock saturation levels and insights on future demand patterns are considered. [16]

Energy system models	Model concept/type	Industrial sector breakdown	Steel demand	Energy demand (if no physical demand is projected)	Recycling/Scrap availability
MESSAGE - Model for Energy Supply Strategy Alternatives and their General Environmental Impact	hybrid model soft-linked to macro-economic general equilibrium model[1]	Thermal and electric demand of total industry, non-energy use, cement process emissions[1, 3]	Not explicitly modeled	Total energy demand is related to GDP and population, based on historical energy intensity trends[3]	Recycling is not considered[3]
GEM-E3 - General Equilibrium Model for Economy-Energy-Environment	general equilibrium[1]	Ferrous metals, non-ferrous metals, chemicals, paper, nonmetallic minerals, electric goods, transport equipment, other equipment, consumer goods industries[9]	The production is modeled through KLEM (capital, labour, energy and materials) production functions. For each production factor (including energy) a derived demand is calculated that is consistent with firms profit maximization.[13, 9]	-	Recycling is not considered[9]
IMAGE - Integrated Model to Assess the Global Environment	partial equilibrium, hybrid integrated assessment simulation model with detailed representation of energy, land and water use[1,2]	**Iron and steel**, cement, other[3]	Steel consumption is described as a function of per capita economic activity[4]	-	Scrap use is limited by supply and the required quality of steel needed for certain applications. Scarp availability is estimated with an analysis of the steel flows in an economy. [4,5]

Energy system models	Model concept/type	Industrial sector breakdown	Steel demand	Energy demand (if no physical demand is projected)	Recycling/Scrap availability
AIM-CGE - Asia-Pacific Integrated Model	general equilibrium model with technology detailed modules for the power sector[1]	**Iron and steel**, chemicals, non-metallic minerals, food processing, pulp and paper, construction, others[3]	Modeled in monetary and not in physical terms	For long-term projections a Constant Elasticity Substitution (CES) function is usually used. Industrial activities have substitution between energy and value-added. The other option uses bottom-up energy technological information and the energy demand is explicitly determined by detailed technologies. [1]	Recycling is not considered[3]
REMIND - Regional Model of Investments and Development	general equilibrium, hybrid model with a detailed energy system module[1,2]	The industrial sector is a part of the stationary sector that also includes the residential and commercial sectors.[1, 7]	Not explicitly modeled	Determined based on GDP growth, autonomous energy efficiency improvements, and the elasticities of substitution between capital and energy and between industry and the commercial, residential and transport sectors.[1,7]	Recycling is not considered[3]

Energy system models	Model concept/type	Industrial sector breakdown	Steel demand	Energy demand (if no physical demand is projected)	Recycling/Scrap availability
WITCH - World Induced Technical Change Hybrid	general equilibrium, hybrid model including a detailed energy sector.[1,2]	The industrial sector is part of the non-electric sector which also covers the transportation, residential and commercial sectors.[1,8]	Not explicitly modeled	The energy use in the stationary sector is defined through a CES nest.[8]	Recycling is not considered[9]
DNE21+	partial equilibrium	**Iron and steel**, cement, pulp and paper, aluminium, some chemicals (ethylene, propylene and ammonia) and petrochemicals[1,3]	The per capita apparent steel consumption is correlated to the evolution of GDP per capita, trends in industry structure per region and government planning reports. [9,1]	-	Scenarios are assumed with maximum and minimum scrap-based EAF steel production levels. The volumes of scrap are exogenously given in a scenario, but scrap recycling for EAF route is endogenously determined within fixed upper and lower limits.[3,1,9]
GCAM - Global Change Assessment Model	partial equilibrium, hybrid IAM with technology-rich representations of the economy, energy sector, land use and water use. [2, 10]	Cement, nitrogenous fertilizers, others. A single homogeneous industrial good is produced from energy services and feedstocks. In regional GCAM versions (USA, China and Brazil) there are 10 industrial subsectors. [9]	The cement and nitrogenous fertilizer sectors are modeled in physical terms driven by GDP and land use, respectively. For the rest of the industry, regional population and labor productivity assumptions generate the regional GDP that drives the energy use. [9, 10]	-	Not explicitly modeled but opportunities in recycling growth influence the assumed improvement rates for each region's generic industrial service technologies in several industries. Specifically, iron and steel has recycling in some form as a means of future

Energy system models	Model concept/type	Industrial sector breakdown	Steel demand	Energy demand (if no physical demand is projected)	Recycling/Scrap availability
					technology efficiency improvement. [9]
Imaclim-R	general equilibrium, hybrid CGE model with sectoral bottom-up modules.[2,3]	Energy-intensive vs. non energy intensive industries. [3]	The industrial sector production results endogenously from the comparison supply and demand in the general equilibrium framework. [9]	-	Not explicitly modeled[3]

[1](ADVANCEwiki); [2](IIASA, 2014); [3](Edelenbosch et al., 2017); [4] (van Ruijven et al., 2016); [5](Neelis and Patel, 2006); [6] (Fujimori et al., 2014); [7](Luderer et al., 2015); [8](WITCH, 2017); [9]stock-taking exercise; [10](GCAM, 2017); [13](Capros et al., 2013); [15](Anandarajah et al., 2011); [16](Morfeldt et al., 2013); [19](OECD/IEA, 2016); [20](Loulou and Labriet, 2008); [21](Keramidas et al., 2017).

* SAAM is not a part of ETSAP-TIAM but has been used in conjunction with TIAM to evaluate the steel demand and scrap availability.

Appendix 6B Results of regression analysis

Table 6-6 Regression analysis results for the transportation activity sector

	S_{sat}	a	b	Assumptions	Constrained S_{sat}?	Std. deviations (tonnes/capita)	R^2
Canada	2.3639	-0.1000	0.4457	straight line	-	-	-
United States	2.0350	0.1000	0.4456	straight line	-	-	
Mexico	0.9000	1.8908	0.0001		Yes	0.02	0.85
Central America	1.4341	8.8352	0.0018		No	0.19	0.71
Brazil	0.9000	3.2131	0.0001		Yes	0.06	0.67
Rest of South America	1.3738	2.0909	0.0000		No	0.01	0.18
Northern Africa	0.9000	3.4086	0.0004		Yes	0.02	0.84
Western Africa	0.8798	3.9498	0.0002	Decreasing steel stocks, similar development with Rest of Southern Africa is assumed	-	-	-
Eastern Africa	0.8798	3.9498	0.0002	Decreasing steel stocks, similar development with Rest of Southern Africa is assumed	-	-	-
South Africa	0.8798	3.9498	0.0002	Decreasing steel stocks, similar development with Rest of Southern Africa is assumed	-	-	-
Western Europe	1.7188	3.0709	0.0002		No	0.03	0.98
Central Europe	0.8832	6.9627	0.0022		No	0.17	0.12
Turkey	0.9000	3.4747	0.0003		Yes	0.06	0.72
Former USSR	0.8832	6.9627	0.0022	similar development with Central Europe	-	-	-
Middle East	2.0511	3.0397	0.0001		Yes	0.01	0.94
India	2.1676	4.5083	0.0003		No	0.00	0.97
Korea region	0.9000	1.5009	0.0001		Yes	0.09	0.70
China region	0.9000	2.7941	0.0004		Yes	0.02	0.92
Southeastern Asia	1.4451	3.3434	0.0003		No	0.01	0.96
Indonesia region	0.9000	4.1883	0.0006		Yes	0.01	0.92
Japan	0.9913	-45.2037	0.0016	good fitting not possible with an S-shaped curve/assuming a straight line	-	-	-
Oceania	1.6285	0.1000	0.7624	straight line	-	-	-
Rest of South Asia	1.4451	3.3434	0.0003	similar development with Southeastern Asia	-	-	-

Rest of Southern Africa	0.8798	3.9498	0.0002		No	0.00	0.11

Table 6-7 Regression analysis results for the construction activity sector

	S_{sat}	a	b	Assumptions	Constrained S_{sat}?	Std. deviations (tonnes/capita)	R^2
Canada	8.4277	3.1683	0.0002		No	0.14	0.99
United States	10.5635	6.5674	0.0004		No	0.10	0.92
Mexico	5.6000	4.7722	0.0003		Yes	0.11	0.89
Central America	5.6000	4.8515	0.0004		Yes	0.05	0.75
Brazil	5.6000	4.5803	0.0004		Yes	0.14	0.82
Rest of South America	5.6000	3.4512	0.0002		Yes	0.12	0.54
Northern Africa	5.6000	4.3747	0.0005		Yes	0.07	0.83
Western Africa	5.6000	5.4555	0.0008	Decreasing steel stocks, similar development with Rest of Eastern Africa is assumed	-	-	-
Eastern Africa	5.6000	5.4555	0.0008		Yes	0.02	0.80
South Africa	8.0122	1.3901	0.0000		Yes	0.28	0.00
Western Europe	9.4972	1.6784	0.0001		No	0.08	0.99
Central Europe	5.6000	1.9298	0.0004		Yes	0.26	0.94
Turkey	5.6000	4.3165	0.0003		Yes	0.19	0.74
Former USSR	5.6000	1.9298	0.0004	similar development with Central Europe	-	-	-
Middle East	5.6000	3.5935	0.0002		Yes	0.04	0.97
India	5.6000	3.9326	0.0005		Yes	0.02	0.93
Korea region	7.9486	3.8417	0.0003		No	0.16	0.99
China region	5.6000	2.9519	0.0004		Yes	0.11	0.94
Southeastern Asia	5.6000	3.6249	0.0004		Yes	0.02	0.98
Indonesia region	5.6000	5.4353	0.0007		Yes	0.02	0.93
Japan	12.0000	2.9283	0.0001		Yes	0.40	0.97
Oceania	5.8348	4.4774	0.0003		No	0.13	0.98
Rest of South Asia	9.4093	5.7572	0.0008		Yes	0.00	0.98
Rest of Southern Africa	8.0122	1.3901	0.0000	Assumed similar to South Africa	-	-	-

Table 6-8 Regression analysis results for the machinery activity sector

	S_{sat}	a	b	Assumptions	Constrained S_{sat}?	Std. deviations (tonnes/capita)	R^2
Canada	1.4870	2.7641	0.0002		No	0.04	0.90
United States	1.0403	0.1000	0.0297	straight line	-	-	-
Mexico	2.2376	4.6168	0.0003		No	0.05	0.90
Central America	0.4923	3.5854	0.0007		No	0.03	0.76
Brazil	0.5644	4.3017	0.0007		No	0.04	0.86
Rest of South America	0.5969	2.7702	0.0005		No	0.04	0.49
Northern Africa	0.5210	5.3805	0.0015		No	0.03	0.95
Western Africa	0.5000	2.1210	0.0001		Yes	0.01	0.17
Eastern Africa	0.5000	3.3027	0.0007		Yes	0.002	0.54
South Africa	1.2610	3.7797	0.0003	similar development with Rest of Southern Africa	-	-	-
Western Europe	0.9812	3.9346	0.0003		No	0.01	0.98
Central Europe	0.9426	5.2404	0.0015		No	0.13	0.46
Turkey	0.9125	4.3929	0.0005		No	0.05	0.96
Former USSR	0.9426	5.2404	0.0015	similar development with Central Europe	-	-	-
Middle East	2.2257	3.1131	0.0002		No	0.02	0.97
India	0.5000	2.0220	0.0006		Yes	0.01	0.97
Korea region	3.4937	3.4647	0.0003	Although the Ssat is higher than the range shown in Table2 (main article), very high stocks are estimated for current years	No	0.09	0.99
China region	1.0418	2.1121	0.0008		Yes	0.03	0.99
Southeastern Asia	1.0070	2.6282	0.0005		No	0.01	0.99
Indonesia region	0.5000	3.6211	0.0008		Yes	0.01	0.93
Japan	0.5697	-44.1218	0.0000	good fitting not possible with an S-shaped curve/assuming a straight line	-	-	-
Oceania	2.2007	5.7909	0.0004		No	0.05	0.96
Rest of South Asia	2.4000	4.3575	0.0005		Yes	0.03	0.85
Rest of Southern Africa	1.2610	3.7797	0.0003		No	0.00	0.69

Table 6-9 Regression analysis results for the Others activity sector

	S_{sat}	a	b	Assumptions	Constrained S_{sat}?	Std. deviations (tonnes/capita)	R^2
Canada	0.5712	10.9783	0.0007		No	0.03	0.57
United States	0.5712	10.9783	0.0007	similar development with Canada	-	-	-
Mexico	0.4118	3.8269	0.0003		No	0.01	0.93
Central America	0.4000	4.7055	0.0005		Yes	0.01	0.80
Brazil	0.4000	3.1162	0.0002		Yes	0.01	0.8
Rest of South America	0.4000	2.3054	0.0001		No	0.01	0.49
Northern Africa	0.4000	3.5942	0.0005		Yes	0.01	0.84
Western Africa	0.4000	4.0909	0.0003		Yes	0.02	0.03
Eastern Africa	0.7995	6.0297	0.0011		Yes	0.001	0.59
South Africa	0.4711	4.7750	0.0004	Decreasing stocks, similar development with Rest of Southern Africa	-	-	-
Western Europe	0.5688	11.8642	0.0009		No	0.02	0.66
Central Europe	0.3484	8.8002	0.0028		No	0.07	0.42
Turkey	0.4000	3.5192	0.0003		Yes	0.03	0.74
Former USSR	0.3484	8.8002	0.0028	similar development with Central Europe	-	-	-
Middle East	0.9000	3.3452	0.0002	-	Yes	0.01	0.95
India	0.4000	3.4368	0.0005		Yes	0.00	0.97
Korea region	1.1603	3.5347	0.0003	Although the Ssat is higher than the range shown in (Table 2 main article), very high stocks are estimated for current years	No	0.03	0.99
China region	0.4000	2.3055	0.0005		Yes	0.01	0.96
Southeastern Asia	0.4000	3.2789	0.0004		Yes	0.00	0.97
Indonesia region	0.4000	4.1591	0.0006		Yes	0.00	0.90
Japan	0.5394	12.9915	0.0010		Yes	0.02	0.76
Oceania	0.7240	28.7227	0.0019		No	0.04	0.35
Rest of South Asia	0.6677	4.9650	0.0006		Yes	0.00	0.67
Rest of Southern Africa	0.4711	4.7750	0.0004		No	0.00	0.76

Appendix 6C Lifetimes used by region and by sector

In the transportation sector, the groups “Long”, “Medium” and “Short” Lifetimes have an average lifetime of 26, 20 and 10 years, respectively. The Canada, United States, and Western Europe regions are in the “Medium Lifetime” group, while the regions Rest of South Asia, India and the African regions are in the “Long Lifetime” group (see Table 6-10). In general, countries with developing economies tend to use their fleets longer. Although the average service life of passenger cars in India is currently short (recent government regulations setting an age limit of 10 years for diesel and 15 years for petrol cars in Delhi) (Goel et al., 2016), it was much higher a few years ago, 20 years in 2005 (Shyam et al., 2006). Transport equipment in Korea had a relatively long lifetime in the 1970s, but also decreased with the rapid economic growth (Rincon-Aznar, 2017). The Netherlands, Germany and the U.S. have an average lifetime for passenger cars between 5 and 9 years (Rincon-Aznar, 2017).

In the construction sector, the groups “Long”, “Medium” and “Short” Lifetimes have an average lifetime of 94, 50 and 38 years, respectively. Most regions are in group “Long Lifetime” (see Table 6-10). A great share of steel goes to the construction of buildings and infrastructure where lifespans are long, ranging from many decades to even centuries (Müller et al., 2007). An average lifetime of 126 years was suggested by Bohne et al. (2006) for Norwegian dwellings, while in Canada 28% of infrastructure is estimated to currently age between 80 and 100 years (Rincon-Aznar, 2017). In this analysis, few regions, such as South Africa, Turkey, Korea, and Japan are in group Short. These are the regions found by Pauliuk et al. (2013a) to have large scrap generation. In the case of Korea this could be explained as the buildings constructed within the period of high economic growth (1970-2000), became in the beginning of our century targets of demolition and reconstruction while having a mean lifespan of 22 years (Seo and Hwang, 2011). Another study estimated the lifetime of Korean residential buildings at 35 years until 1985, and then it slowly increased to 50 years (Rincon-Aznar, 2017). In the case of Japan, which had to replace all the building stock after World War II, studies indicate very short lifetimes for reinforced concrete residential and commercial buildings of 50 and 35 years, respectively (Komatsu et al., 1994). Short lifetimes were also reported in Japan for transport and machineries, at 12 years for passenger cars (14 years for trucks) and 12 years for machineries (Igarashi et al., 2008).

Table 6-10 Global region assignment to the “Long Lifetime”, “Medium Lifetime” and “Short Lifetime” groups

	Transport	Construction	Machinery	Other
	“Long”=26; “Medium”=20; “Short”=10	“Long”=94; “Medium”=50; ”Short”=38	“Long”=39; “Medium”=30; “Short”=16	“Long”=20; “Medium”=15; “Short”=8
Canada	Medium	Long	Medium	Medium
United States	Medium	Long	Medium	Medium
Mexico	Medium	Medium	Medium	Medium
Central America	Long	Long	Long	Long
Brazil	Short	Medium	Short	Short
Rest of South America	Long	Long	Long	Long
Northern Africa	Long	Long	Long	Long
Western Africa	Long	Long	Long	Long
Eastern Africa	Long	Long	Long	Long
South Africa	Short	Short	Short	Short
Western Europe	Medium	Long	Long	Short
Central Europe	Short	Medium	Short	Short
Turkey	Short	Short	Medium	Short
Former USSR	Medium	Medium	Long	Medium
Middle East	Long	Long	Long	Long
India	Long	Long	Long	Long
Korea region	Short	Short	Short	Short
China region	Long	Long	Long	Long
Southeastern Asia	Long	Long	Long	Long
Indonesia region	Medium	Long	Medium	Medium
Japan	Short	Short	Short	Short
Oceania	Long	Long	Long	Long
Rest of South Asia	Long	Long	Long	Long
Rest of Southern Africa	Long	Long	Long	Long

For China, the average household lifetime greatly depends on the period they were built and are much shorter than in developed countries (Zhou et al., 2019). Average lifetimes were estimated by (Hu et al., 2010) at 20 years for rural houses built before 1978 (poor housing conditions), at 50 years for urban houses built before 1966 and at 15 years for urban houses built during 1966-1971 (China’s cultural revolution), while after 1978 the lifetimes are considered to have greatly increased. A combination of various reasons is responsible for the short lifetimes, e.g. the use of inferior quality of building materials, poor design standards, and the inappropriate fast demolition of buildings as a result of rapid urbanization and city rebuilding (Zhou et al., 2019). In this analysis, although a higher average lifetime is considered for China (group “Long Lifetime”) the results on future annual consumption are not considered to have been greatly affected since old stocks in the past were low.

There are six regions, Brazil, Central America, South Africa, Turkey, Korea, and Japan that for most activity sectors are in group “Short Lifetime”. Although, as described above, a period of strong economic growth could explain the short lifetimes for some regions, it is unclear whether this argument holds for every region. The assignment of lifetimes in (al P. e., 2013) was based on scrap generation volumes and ignores uncertainties in the iron content of traded goods, formation of obsolete stocks, and misreporting of scrap flows, all of which can lead to overestimated or underestimated lifetimes (Pauliuk, personal communication).

In the machinery sector, the groups "Long", "Medium" and "Short" Lifetime have an average lifetime of 39, 30 and 16 years, respectively. Most regions are in group "Long Lifetime". A high average lifetime for this sector could be explained by a higher share of industrial machinery and/or the presence of old industrial stocks. A low average lifetime could be explained by the greater reliance in services and/or a great rate of demolitions and possible replacement of industrial stocks in past years.

In the others sector, the groups "Long", "Medium" and "Short" Lifetimes have an average lifetime of 20, 15 and 8 years, respectively. Most regions are in group "Long Lifetime". In the six regions appearing in group "Short Lifetime" Western Europe is also added. Other developed regions, such as Canada and the U.S are in group "Medium Lifetime". It has been observed that lifetimes in developed countries used to be longer in the 1990's and then decreased (Aznar, 2017).

In the "Converging Lifetime" group, the average lifetime is for all sectors similar to group "Medium Lifetime". Only for the construction sector the average lifetime is 71 years (lying between group "Long" and group "Medium" Lifetime).

Appendix 6D Steel stock projections per IMAGE region

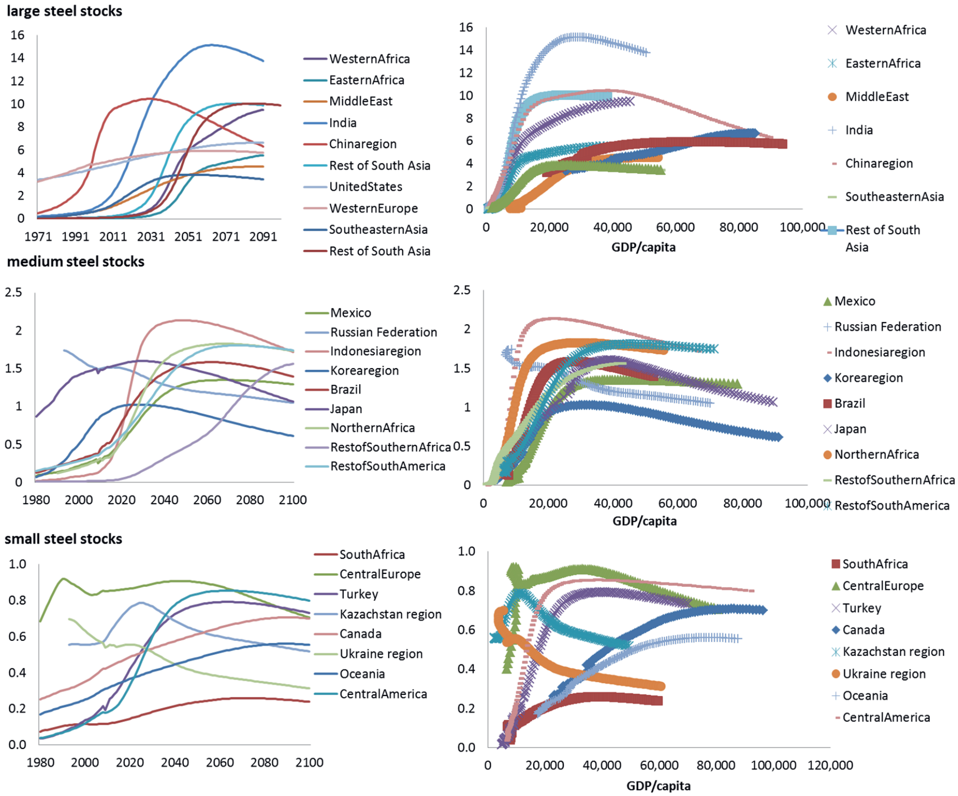

Figure 6-10 In-use steel stocks projections (in Gtonnes) (left side) and steel stock saturation levels (tonnes/capita) for different income levels (right side) for the 26 regions in IMAGE (spilt into regions with a) large steel stocks, b) medium steel stocks, and c) small steel stocks)

7 Summary and conclusions

7.1 Scope of the thesis

Despite past energy efficiency improvements and decarbonation efforts, the industrial sector is still responsible for 40% of global energy consumption and more than 43%[59] of global CO_2 emissions (IEA, 2020a). From 1980 onwards, the demand for industrial products has sharply increased, driving GHG emissions to record high levels. In the coming decades, energy demand and emissions are expected to further increase driven by the growing needs for bulk materials in countries with large populations that are still in their first stages of economic development. To limit the temperature growth to 1.5°C, industrial GHG emissions will need to drastically decrease to net zero emissions by 2050-70.

In the first part of the thesis available data from international statistics and information on energy efficiency improvement options is utilized to identify the role industrial energy efficiency can play in limiting the ever-rising industrial energy demand. In the second part of the thesis, it is investigated how the industrial sector is represented in global long-term energy models and methods are developed for better capturing energy efficiency, material efficiency and material demand to improve the models industry representation. The main results and conclusions are summarized in the following paragraphs.

7.2 Potentials for energy efficiency improvement in energy intensive industries

Energy efficiency is considered a key measure for reducing industrial energy demand. Two chapters are dedicated in answering the first research sub-question:

What are the global and regional, current and future potentials for energy reduction in the industrial sector when considering the wide adoption of currently available energy saving measures?

In Chapter 2, the energy use of six industrial sectors (iron and steel, chemicals and petrochemicals, primary aluminium, non-metallic minerals, paper, pulp and printing, and others) is analyzed and by applying Best Available Technologies (BATs) and Best Practice Technologies (BPTs) energy efficiency levels and increased levels of recycling the energy demand in ten regions under a reference (representing a business-as-usual scenario) and a low energy demand scenario for the period 2008-2050 is determined. First, an analysis of the regional energy intensity of the manufacturing processes is overtaken based on the available international statistics and gaps are filled with data available in literature. To identify the potential for energy savings, the regional energy intensities are compared to the BAT level and to a maximum recycling level. Future scenarios are then developed that link industrial activity to the Gross Domestic Product (GDP) developments. In the reference scenario, only autonomous energy efficiency improvements (energy efficiency adopted because new plants

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[59] It includes the CO_2 emissions from electricity and heat generation. By not allocating these emissions to the industrial sector the industrys' share on global CO_2 emissions drops to 23% (IEA, 2020a).

tend to be more efficient than the older, they replace) is considered as policies remain untightened. In the low energy demand scenario, all BAT technologies are implemented, and recycling is at the maximum level. In the reference scenario, global industrial energy demand (including coke ovens and blast furnaces and excluding feedstocks) is found to increase from 105 EJ in 2008 to 185 EJ in 2050. It is estimated that the wide implementation of BAT measures and increased recycling can halve the global annual growth of industrial energy demand from 1.4%/a to 0.7%/a. The growth remained the highest in India and the Other non-OECD Asia (2.3%/year and 1.8%/year), followed by Middle East (1.2%/year), Africa (1.0%/year), Latin America (0.8%/year), and China (0.7%/year) while energy demand increase was the lowest in OECD Asia Oceania, OECD Americas and OECD Europe.

It is shown that the wide implementation of energy saving measures can result in substantial energy savings, calculated at 44 EJ in 2050; one quarter of that years global industrial energy consumption. The most energy savings are available in the less energy intensive industrial sub-sectors (Others industrial sub-sector) and then follow the energy intensive iron and steel and the chemical and petrochemical industries. The largest share of the global estimated technical savings potentials, 36%, is identified in China, and then follow the Transition economies (15%) and India (9%).

Chapter 3 investigates in detail the energy efficiency potential in one industrial sub-sector: the primary aluminium industry. In a first step, the energy use per main process (alumina refining and aluminum smelting) in the aluminium production chain is assessed and then, data is collected from international statistics and available literature. The analysis is performed on a country level to capture possible deviations on the industrial energy efficiency level. In a second step, the main energy efficiency improving measures per process step are distinguished and energy and greenhouse gas abatement curves are constructed to identify the cost-effectiveness of the energy efficiency potential.

The primary energy demand (mainly fuel) for alumina refining in a reference scenario is found to more than double from about 960 PJ in 2009 to 1,850 in 2050. In the same scenario, greenhouse gas emissions from the combustion of fossil fuels used for the calcination of bauxite is found to increase from 80 $MtCO_2$ in 2009 to 150 $MtCO_2$ by 2050. Energy efficiency measures can decrease the 2050 energy demand by 12%, of which 45% is cost-effective (the cost of saving one GJ of energy is lower than the cost of buying one GJ of energy). Similar is the impact on greenhouse gas emissions. In a frozen efficiency scenario, the actual technical potential is found to be much higher, identified at 31% for energy demand, of which 60% is cost-effective. The reference scenario assumes that a part of the cost-effective technical energy savings potential in the frozen efficiency scenario is already adopted limiting the energy savings potential to 12%. The primary energy demand (only electricity) for aluminium smelting in the reference scenario is found to more than double, from 3,600 PJ in 2009 to 9,400 PJ in 2050. Greenhouse gas emissions from electricity generation and process-related emissions is found to increase from 330 $MtCO_{2\text{-eq}}$ in 2009 to 856 $MtCO_{2\text{-eq}}$. Energy efficiency measures can decrease the energy demand in year 2050 only by 0.9% and greenhouse gas emissions by 0.6%. In a frozen efficiency scenario, the energy efficiency and greenhouse gas reduction potentials are much higher (9% and 9%, respectively) but in the reference scenario where industry continues improving its energy efficiency according to historical rates almost all measures are adopted. In Chapter 3, the energy savings potentials under a reference scenario are found to be higher (21% for alumina refining and 8% for aluminium). There are two main reasons: i) in Chapter 3 it is assumed that that all new capacity alumina installed capacity in China and Russia adopts the energy efficient Bayer process limiting therefore the future energy savings potentials and ii) only the adoption of currently available measures was taken into consideration.

Overall, the 2050 technical primary energy savings potential is 307 PJ, equivalent to about 3% of the 2050 primary energy use; 222 PJ can be saved in alumina refining and 86 PJ in aluminium smelting. The highest energy savings potentials in this industry exists in the lower energy intensive and not sufficiently investigated alumina refining industry. Concerning aluminium smelting, if no new technologies become available in the coming years there will only be a small potential for energy efficiency improvements, and the only way to reduce the emissions would be through the decarbonization of the electricity used.

7.3 Capturing key industrial characteristics in long-term energy models for improved modeling results

Long-term energy models are extensively used for scenario development in an effort to understand and evaluate possible sector/system interactions and changes in the global energy system. Three thesis chapters are dedicated in answering the research sub-question:

What is the representation of the industrial sector in long-term energy models and what impact does the inclusion of key industrial characteristics have on model projections?

Chapter 4 tries to understand differences in industrial projections among models. For this, data on model structure, system boundaries and key inputs such as assumptions used on energy and demand drivers, and policy measures in main long-term energy models are collected and industrial projections are compared in two scenarios; a baseline scenario (no new climate policies) and a mitigation scenario (stabilization level at 450 ppm CO_2-eq). A key difference identified between models is the breakdown of the industrial sector, and more specifically the explicit representation of material demand, demand drivers, technologies included and the assumptions on energy efficiency. The models without a sectoral breakdown, are less detailed, and use economic and demographic drivers to project energy demand without explicitly acounting for material demand. Modeling material demand would allow for an explicit representation of several industrial processes, energy intensities, energy efficiency technologies and other greenhouse gas mitigation measures. Another key difference identified is on the system boundaries used with some models including energy use for feedstock purposes, and/or coke ovens, blast furnaces and refineries and others do not. Such differences, when not transparent, can hinder model intercomparison results.

Comparing the energy demand projections of different models revealed both similarities and disagreements. It is found that energy intensity (w.r.t GDP) in Non-OECD regions is projected to decrease more rapidly (1.8-2.2%) in all models over the coming century than in the 1970-2010 period (0.6%). Other similarities found are on the energy demand projections for OECD countries and on the fuel shares. The 2100 energy demand projections in OECD countries range between 36 and 71 EJ, and the share of electricity increases by 10-20%, while the share of fossil fuels slightly decreases. Despite these similarities, models are found to disagree on the projected carbon emission pathways. A broad range, between 7.5 and 24 Gt/yr in 2100, is observed across the models. This can be explained by different base year assumptions in terms of fuel shares, energy consumption and accompanying emissions, as well as on the saturation level of industrial energy demand assumed for Non-OECD countries, which is a key uncertainty across models. Comparing the projections in the mitigation scenarios also shows a range of 10-50% with the less detailed models being more flexible in fuel switching than the models with explicit sub-sector representation and technology details.

It can be concluded that sub-sector specific information could improve projections and increase the ability to assess sector specific mitigation policies. It can indicate for example what are the realistic energy intensity improvements, adoption levels of certain technologies, material usage and the penetration of less carbon intensive fuels. For instance, comparing the projected specific energy consumption of cement production in the mitigation scenarios to state-of-the-art knowledge showed that there is indeed scope to considerably reduce energy demand compared to the models' baseline scenarios.

In Chapter 5, the state-of-the-art modeling of the cement industry in long-term energy models is compared, and key areas for improvement and the impact the inclusion of key industry characteristics can have on model results are analyzed. The cement industry was selected because it covers a significant share of industrial energy demand and GHG emissions, while it is also a relatively simple industry to model due to the limited complexity of the processes used, limited trade between countries and especially regions, and the significant data availability regarding the energy efficiency technologies that can be adopted. It is found that most models do not model the cement industry specifically but the non-metallics minerals sector as a whole. The non-metallics sector is comprised of a variety of industries such as glass, lime, and bricks, next to cement, the largest sub-sector. Industries that have in general very diverse characteristics. Out of the eight long-term energy models assessed, only DNE 21+ and IMAGE explicitly model the cement industry, while two models (Imaclim-R and MESSAGE) do not have a representation of the cement industry or the non-metallic minerals sector. It was also found that for the models with a cement industry representation, two sector specific greenhouse gas mitigation measures are often not explicitly accounted for, namely: i) retrofitting and ii) clinker to cement ratio reduction. It is found that the inclusion of retrofitting older plants with energy efficiency technologies can save an additional 853 $MtCO_2$ in a reference scenario and about 920 $MtCO_2$ in a mitigation scenario in the 2010-2040 period (about 4 and 5% of total CO_2 emissions released in this period). All the retrofitting measures considered were identified as "cost-effective" (i.e. it costs less to adopt the energy efficiency measure than not to) or else known as "low-regret" measures, measures that are usually ignored by energy models. Linking the availability of blast furnace slag and fly ash (i.e. main clinker supplementing materials) to the potential of clinker to cement reduction significantly affects the model results. It is calculated that if all available supplementary materials are used, with product restrictions considered, the 2100 energy demand for cement making is 15% lower than originally estimated in a reference scenario. In a mitigation scenario, because many coal-fired power plants are modeled to close, the future availability of fly ash will be limited and therefore also the potential for energy savings from clinker substitution in the cement industry. The limited fly ash availability can drive the need to mine historic fly ash "deposits", e.g. fly ash ponds at power stations, and to better exploit other clinker substituting materials such as BF slags that are currently only partly utilized (a large share of BF air dried, so its potential in the cement industry is not fully exploited). In this scenario, energy demand and greenhouse gas emissions in 2100 is found to be 14% higher than when estimated without capturing the impact that policies in the energy sector can have to the cement industry. Fully modelling the interrelations between sectors (and hence an accurate modeling of potentials) and fully capturing the energy efficiency potentials (also in the form of retrofitting) requires more detailed modeling of industries in long-term energy models.

In Chapter 6, it is investigated how another important, in terms of energy and GHG emissions, industrial sector, the steel industry, is represented in long-term energy models. The steel industry was selected as it is responsible for about one quarter of industrial energy demand and industrial direct CO_2 emissions. It is found that of the twelve models assessed, only seven have a representation of the steel sector, while only five models model the physical demand (in tonnes of product). For making industrial activity projections, long-term energy models commonly couple the annual steel demand to the developments in gross domestic product (GDP). However, literature suggests that in-use steel stocks and not the annual steel consumption, serve as a better indicator of steel demand. Chapter 6 evaluates thereby, how a different approach to estimate future demand projections that is based on the past accumulation of in-use steel stocks can impact model results. It is found that with both approaches (a "flow-based" approach linking annual steel consumption to GDP and a "stock-based" approach linking the in-use steel stocks to GDP) global steel demand increases at similar rates in the first half of the 21st century. However, on the second half of the century projections are found to deviate strongly between the two approaches. With the flow-based approach, the steel demand continues to grow, albeit less drastically, to reach 2,600 Mtonnes/a in 2100 while in the "stock-based" approach, the steel demand is 75% lower estimated at 1,600 Mtonnes. In the second half of the century, in-use steel stocks are found to have reached saturation levels and do not continue to increase, which means that all steel demand can be covered by steel that leaves the accumulated steel stocks (retired steel). Given that steel production has a profound contribution to GHG emissions, this means that IAMs may currently overestimate the industrial emissions in the last half of the century and thereby the investments needed for greenhouse gas mitigation.

7.4 Overall conclusions

Finally, we return to the main research question:

To what degree can energy efficiency improvement decrease industrial energy demand and are key industry characteristics and mitigation measures sufficiently captured in long-term energy models?

It is estimated that despite the historical energy efficiency improvements and the increased recycling efforts, the adoption of energy efficiency technologies/measures and high recycling rates can decrease the global industrial energy demand in the short term by one quarter: from

185 EJ to 140 EJ in 2050. The largest potential for energy savings is identified for non-OECD countries that are found to be responsible for the largest share of future industrial energy demand while the majority of energy savings can be achieved in the Others sector that covers the less energy intensive industries (e.g., machinery, textiles, food and tobacco). The primary aluminium industry, a very energy intensive industry, heavily reliant on electricity which poses the largest share of production costs, has managed in the past years to significantly capture its energy efficiency potential. Continuing the same energy efficiency trends, it is estimated that by 2050 there will be almost no room for energy efficiency improvement in aluminium smelting. On the other hand, the intermediate step in aluminium manufacture, the less energy intensive and fossil fuel reliant, manufacture of alumina, is further away from capturing its technical energy savings potential. It is identified that the future energy savings potential, if current energy efficiency trends continue, drops to 12% for alumina refining and 0.9% for aluminium smelting.

To achieve the identified 44 EJ energy savings potential, all barriers, e.g. economic, technological, or knowledge-based, and organizational, need to be overcome. In addition, the less energy intensive, but not well investigated in terms of their energy profiling and the presence of energy efficient opportunities, industries, alumina refining as an example, need to also implement all energy efficiency opportunities extensively. Finally, although the energy savings potentials are found to be significant, they cannot alone reach the EU goals for 2050, highlighting the fact that more measures, such as low carbon technologies and material efficiency will need to be in place.

After assessing the impact of energy efficiency improvements in the future industrial energy demand this research aimed to investigate whether industry-specific characteristics are taken into consideration in long-term energy models and as a result whether the energy efficiency potentials identified in these models are sufficiently captured. Energy models have a set of multi linkages across different systems aiming to capture and evaluate climate change policies. It is found that industrial details are being captured only in some models with many models representing the industrial sector as a whole, without allowing for industrial details. The strong modeling differences among models can partly explain the also strong disagreements identified from model intercomparisons (16 Gt/yr difference in emissions under the same scenario) with less industry detailed models allowing for greater flexibility when investigating electrification for example. There are key uncertainties for all models, such as the demand saturation of different industrial goods in the different regions, or the penetration level of new technologies, or technology preferences, however, basic linkages e.g., between industrial activity and energy intensity are well possible. There is thereby significant room for improving model projections by adding knowledge on key areas from bottom-up analysis.

This is true even for the models that already have an explicit industrial sub-sector representation. By including the retrofitting of older plants with energy efficient technologies as a carbon mitigation measure in the cement industry, revealed that a non-significant amount of CO_2 emissions can be saved between 2010-2040 in a cost-effective way, a measure that was previously ignored by models. In addition, policies in one sector can influence the CO_2 mitigation potentials in another sector. For example, in a scenario where the energy sector faces out coal-fired power plants, the generation of valuable for other industries by-products will be limited. Such a by-product is fly ash, that can be used by the cement industry to reduce the carbon emissions. Capturing this intersectoral relationship in the model eliminated a previously identified energy savings potential from increased fly ash utilization of about 14%.

Long-term energy models can also profit from studies that assess in detail the material cycles and improve the way they make material demand projections. By using results from Material Flow Analysis (MFA) on steel stock developments and linking it to steel demand model projections revealed a significantly different demand development, especially after 2050 with steel demand significantly decreasing after a certain pick is reached. The use of a different and better demand indicator resulted in a 75% lower demand projection by 2100 consequently affecting all model results, such as energy demand projections, greenhouse gas (GHG) projections, mitigation potentials per technology, investments required, and other system impacts. Finally, to improve the industry modeling results in long-term energy models, key industry specific information needs to be used from bottom studies, key interrelations between sectors need to be identified while material cycle analysis results can be used for deriving better demand indicators.

8 Samenvatting en conclusies

8.1 Reikwijdte van het proefschrift

Ondanks de verbeteringen van de energie-efficiëntie in het verleden en de decarboniseringsinspanningen is de industriële sector nog steeds verantwoordelijk voor 40% van het mondiale energieverbruik en meer dan 43% van de mondiale CO_2-emissies (IEA, 2020a). Vanaf 1980 is de vraag naar industriële producten sterk toegenomen, waardoor de broeikasgasemissies tot recordhoogte zijn gestegen. In de komende decennia zullen de energievraag en de emissies naar verwachting verder toenemen onder invloed van de groeiende behoefte aan bulkmaterialen in landen met een grote bevolking die zich nog in de eerste fasen van hun economische ontwikkeling bevinden. Om de temperatuurstijging tot 1,5°C te beperken, zal de uitstoot van broeikasgassen door de industrie drastisch moeten dalen tot een netto-uitstoot van nul in 2050-70.

In het eerste deel van het proefschrift wordt gebruik gemaakt van beschikbare gegevens uit internationale statistieken en informatie over mogelijkheden om de energie-efficiëntie te verbeteren, om te bepalen welke rol industriële energie-efficiëntie kan spelen bij het beperken van de alsmaar stijgende vraag naar industriële energie. In het tweede deel van het proefschrift wordt onderzocht hoe de industriële sector wordt weergegeven in wereldwijde langetermijnenergiemodellen en worden methoden ontwikkeld om energie-efficiëntie, materiaalefficiëntie en materiaalvraag beter weer te geven om de representatie van de industrie in de modellen te verbeteren. De belangrijkste resultaten en conclusies worden in de volgende paragrafen samengevat.

8.2 Potentieel voor verbetering van de energie-efficiëntie in energie-intensieve industrieën

Energie-efficiëntie wordt beschouwd als een belangrijke maatregel om de industriële energievraag te verminderen. Twee hoofdstukken zijn gewijd aan het beantwoorden van de eerste onderzoeksdeelvraag:

Wat zijn de mondiale en regionale, huidige en toekomstige mogelijkheden voor energiebesparing in de industriële sector, rekening houdend met de brede toepassing van de momenteel beschikbare energiebesparende maatregelen?

In hoofdstuk 2 wordt het energiegebruik van zes industriële sectoren (ijzer en staal, chemie en petrochemie, primair aluminium, niet-metaalhoudende mineralen, papier, pulp en drukkerijen, en overige) geanalyseerd en wordt door toepassing van de beste beschikbare technologieën (BBT's) en de best practice technologieën (BPT's) het energie-efficiëntieniveau en de toename van recyclingniveaus bepaald van de energievraag in tien regio's in een referentiescenario (dat staat voor een business-as-usual-scenario) en een scenario voor een lage energievraag voor de periode 2008-2050. Eerst wordt een analyse gemaakt van de regionale energie-intensiteit van de fabricageprocessen op basis van de beschikbare internationale statistieken en worden lacunes opgevuld met in de literatuur beschikbare gegevens. Om het potentieel voor energiebesparing te identificeren, worden de regionale energie-intensiteiten vergeleken met het BBT-niveau en met een maximaal recyclageniveau. Vervolgens worden toekomstscenario's ontwikkeld waarin de industriële activiteit wordt gekoppeld aan de ontwikkeling van het bruto binnenlands product (BBP). In het referentiescenario wordt alleen rekening gehouden met autonome verbeteringen van de energie-efficiëntie (energie-efficiëntie die wordt bereikt omdat nieuwe installaties doorgaans efficiënter zijn dan de oudere die zij vervangen), aangezien het beleid ongewijzigd blijft. In het scenario van een lage energievraag worden alle BBT-technologieën toegepast en is recycling op het maximumniveau. In het referentiescenario blijkt de wereldwijde industriële energievraag (inclusief cokesovens en hoogovens en exclusief grondstoffen) toe te nemen van 105 EJ in 2008 tot 185 EJ in 2050. Geschat wordt dat de brede toepassing van BBT-maatregelen en meer recycling de wereldwijde jaarlijkse groei van de industriële energievraag kunnen halveren van 1,4%/a tot 0,7%/a. De groei bleef het hoogst in India en Overig niet-OESO-Azië (2,3%/jaar en 1,8%/jaar), gevolgd door het Midden-Oosten (1,2%/jaar), Afrika (1,0%/jaar), Latijns-Amerika (0,8%/jaar), en China (0,7%/jaar), terwijl de toename van de energievraag het laagst was in OESO-Azië-Oceanië, OESO-Noorden-Amerika en OESO-Europa.

Aangetoond wordt dat de brede toepassing van energiebesparende maatregelen kan leiden tot aanzienlijke energiebesparingen, berekend op 44 EJ in 2050; een kwart van het wereldwijde industriële energieverbruik in dat jaar. De meeste energiebesparingen zijn beschikbaar in de minder energie-intensieve industriële subsectoren (Andere industriële subsector) en daarna volgen de energie-intensieve ijzer- en staalindustrie en de chemische en petrochemische industrie. Het grootste deel van het wereldwijd geraamde technische besparingspotentieel, 36%, wordt geïdentificeerd in China, gevolgd door de overgangseconomieën (15%) en India (9%).

Hoofdstuk 3 onderzoekt in detail het energie-efficiëntiepotentieel in één industriële subsector: de primaire aluminiumindustrie. In een eerste stap wordt het energiegebruik per hoofdproces (raffinage van aluminiumoxide en smelten van aluminium) in de aluminiumproductieketen beoordeeld en vervolgens worden gegevens verzameld uit internationale statistieken en beschikbare literatuur. De analyse wordt uitgevoerd op landenniveau om mogelijke afwijkingen van het industriële energie-efficiëntieniveau in kaart te brengen. In een tweede stap worden de belangrijkste maatregelen ter verbetering van de energie-efficiëntie per processtap onderscheiden en worden energie- en broeikasgasreductiecurven geconstrueerd om de kosteneffectiviteit van het energie-efficiëntiepotentieel te bepalen.

De vraag naar primaire energie (voornamelijk brandstof) voor de raffinage van aluminiumoxide blijkt in een referentiescenario meer dan te verdubbelen van ongeveer 960 PJ in 2009 tot 1 850 PJ in 2050. In hetzelfde scenario zal de uitstoot van broeikasgassen door de verbranding van fossiele brandstoffen die worden gebruikt voor het branden van bauxiet, toenemen van 80 $MtCO_2$ in 2009 tot 150 $MtCO_2$ in 2050. Maatregelen voor energie-efficiëntie kunnen de energievraag in 2050 met 12% doen dalen, waarvan 45% kosteneffectief is (de kosten van het besparen van één GJ energie zijn lager dan de kosten van het kopen van één GJ energie). Hetzelfde geldt voor het effect op de uitstoot van broeikasgassen. In een bevroren efficiëntiescenario blijkt het werkelijke technische potentieel veel hoger te liggen, namelijk op

31% voor de energievraag, waarvan 60% kosteneffectief is. In het referentiescenario wordt ervan uitgegaan dat een deel van het kosteneffectieve technische energiebesparingspotentieel in het bevroren efficiëntiescenario reeds is gerealiseerd, waardoor het energiebesparingspotentieel tot 12% wordt beperkt. De vraag naar primaire energie (alleen elektriciteit) voor het smelten van aluminium blijkt in het referentiescenario meer dan te verdubbelen, van 3.600 PJ in 2009 tot 9.400 PJ in 2050. Broeikasgasemissies ten gevolge van elektriciteitsopwekking en procesgerelateerde emissies blijken toe te nemen van 330 $MtCO_2$-eq in 2009 tot 856 $MtCO_2$-eq. Maatregelen voor energie-efficiëntie kunnen de energievraag in 2050 met slechts 0,9% en de broeikasgasemissies met 0,6% doen dalen. In een bevroren efficiëntiescenario liggen de potentiële energie-efficiëntie en broeikasgasreductie veel hoger (respectievelijk 9% en 9%), maar in het referentiescenario waarin de industrie haar energie-efficiëntie blijft verbeteren volgens de historische percentages, worden bijna alle maatregelen genomen. In hoofdstuk 3 wordt geconstateerd dat het energiebesparingspotentieel in een referentiescenario hoger is (21% voor de raffinage van aluminiumoxide en 8% voor aluminium). Hiervoor zijn twee hoofdredenen: i) in hoofdstuk 3 wordt ervan uitgegaan dat alle nieuwe capaciteit voor de productie van aluminiumoxide in China en Rusland wordt geïnstalleerd volgens het energie-efficiënte Bayer-procédé, waardoor het toekomstige energiebesparingspotentieel wordt beperkt, en ii) er is alleen rekening gehouden met de toepassing van momenteel beschikbare maatregelen.

In totaal bedraagt het technische besparingspotentieel voor primaire energie in 2050 307 PJ, wat overeenkomt met ongeveer 3% van het primaire energiegebruik in 2050; 222 PJ kan worden bespaard in de aluminiumoxideraffinage en 86 PJ in de aluminiumsmelterij. Het hoogste energiebesparingspotentieel in deze industrie is aanwezig in de minder energie-intensieve en niet voldoende onderzochte aluminiumoxideraffinage-industrie. Wat het smelten van aluminium betreft, zal er, indien er in de komende jaren geen nieuwe technologieën beschikbaar komen, slechts een klein potentieel voor verbetering van de energie-efficiëntie zijn, en de enige manier om de emissies terug te dringen zou het koolstofvrij maken van de gebruikte elektriciteit zijn.

8.3 Vastleggen van belangrijke industriële kenmerken in langetermijnenergiemodellen voor betere modelresultaten

Lange termijn energiemodellen worden uitgebreid gebruikt voor scenario-ontwikkeling in een poging om mogelijke sector/systeeminteracties en veranderingen in het mondiale energiesysteem te begrijpen en te evalueren. Drie hoofdstukken van het proefschrift zijn gewijd aan het beantwoorden van de onderzoeksdeelvraag:

Wat is de representatie van de industriële sector in lange termijn energiemodellen en welke impact heeft het opnemen van belangrijke industriële kenmerken op de modelprojecties?

Hoofdstuk 4 probeert de verschillen in industriële projecties tussen modellen te begrijpen. Daartoe worden gegevens verzameld over de modelstructuur, de systeemgrenzen en de belangrijkste inputs, zoals de gebruikte aannames over energie- en vraagsturing en beleidsmaatregelen in de voornaamste langetermijnenergiemodellen, en worden de industriële prognoses vergeleken in twee scenario's: een basisscenario (geen nieuw klimaatbeleid) en een mitigatiescenario (stabilisatieniveau op 450 ppm CO_2-eq). Een belangrijk verschil tussen de modellen is de uitsplitsing van de industriële sector, en meer bepaald de expliciete weergave van de materiaalvraag, de drijvende krachten achter de vraag, de opgenomen technologieën en de aannamen inzake energie-efficiëntie. De modellen zonder sectorale uitsplitsing zijn minder gedetailleerd en maken gebruik van economische en demografische drijfveren om de energievraag te ramen zonder expliciet rekening te houden met de materiaalvraag. Modellering van de materiële vraag zou een expliciete weergave mogelijk maken van verschillende industriële processen, energie-intensiteiten, energie-efficiëntietechnologieën en andere broeikasgasreducerende maatregelen. Een ander belangrijk verschil dat werd vastgesteld, betreft de systeemgrenzen die worden gebruikt: sommige modellen houden rekening met het energiegebruik voor grondstoffen en/of cokesovens, hoogovens en raffinaderijen, terwijl andere dat niet doen. Dergelijke verschillen kunnen, wanneer zij niet transparant zijn, de onderlinge vergelijking van modelresultaten belemmeren.

Een vergelijking van de prognoses van de energievraag van verschillende modellen bracht zowel overeenkomsten als verschillen aan het licht. Gebleken is dat de energie-intensiteit (t.o.v. BBP) in niet-OESO-regio's naar verwachting in de komende eeuw in alle modellen sneller zal afnemen (1,8-2,2%) dan in de periode 1970-2010 (0,6%). Andere gevonden overeenkomsten betreffen de prognoses van de energievraag voor de OESO-landen en de brandstofaandelen. De prognoses voor de energievraag in de OESO-landen voor 2100 liggen tussen 36 en 71 EJ, en het aandeel van elektriciteit neemt toe met 10-20%, terwijl het aandeel van fossiele brandstoffen licht daalt. Ondanks deze gelijkenissen blijken de modellen van mening te verschillen over de voorspelde koolstofemissieroutes. De modellen vertonen een grote variatie, tussen 7,5 en 24 Gt/jaar in 2100. Dit kan worden verklaard door verschillende aannames voor het referentiejaar in termen van brandstofaandelen, energieverbruik en bijbehorende emissies, alsmede over het verzadigingsniveau van de industriële energievraag in niet-OESO-landen, hetgeen een belangrijke onzekerheid is in de modellen. Een vergelijking van de prognoses in de mitigatiescenario's laat ook een verschil zien van 10-50%, waarbij de minder gedetailleerde modellen flexibeler zijn bij de overschakeling op andere brandstoffen dan de modellen met een expliciete vertegenwoordiging van subsectoren en technologische details.

Er kan worden geconcludeerd dat subsectorspecifieke informatie de prognoses kan verbeteren en het vermogen om sectorspecifiek mitigatiebeleid te beoordelen, kan vergroten. Zo kan bijvoorbeeld worden aangegeven wat de realistische verbeteringen zijn van de energie-intensiteit, de niveaus van invoering van bepaalde technologieën, het materiaalgebruik en de penetratie van minder koolstofintensieve brandstoffen. Uit een vergelijking van het geraamde specifieke energieverbruik van de cementproductie in de mitigatiescenario's met de meest recente kennis blijkt bijvoorbeeld dat er inderdaad ruimte is om de energievraag aanzienlijk te verminderen in vergelijking met de basisscenario's van de modellen.

In hoofdstuk 5 wordt de state-of-the-art modellering van de cementindustrie in langetermijnenergiemodellen vergeleken, en worden de belangrijkste gebieden voor verbetering en de impact die het opnemen van belangrijke kenmerken van de industrie op de modelresultaten kan hebben, geanalyseerd. De cementindustrie werd geselecteerd omdat zij een aanzienlijk deel van de industriële energievraag en broeikasgasemissies voor haar rekening neemt, terwijl het ook een relatief eenvoudige bedrijfstak is om te modelleren vanwege de beperkte complexiteit van de gebruikte processen, de beperkte handel tussen landen en vooral regio's, en de aanzienlijke beschikbaarheid van gegevens met betrekking tot de energie-efficiëntietechnologieën die kunnen worden toegepast. Gebleken is dat in de meeste modellen niet de cementindustrie specifiek wordt gemodelleerd, maar de sector van de niet-metaalhoudende mineralen in zijn geheel. De sector van de niet-metaalhoudende delfstoffen bestaat uit een verscheidenheid van industrieën zoals glas, kalk en bakstenen, naast cement, de grootste subsector. Dit zijn industrieën die over het algemeen zeer uiteenlopende kenmerken hebben. Van de acht beoordeelde langetermijnenergiemodellen maken alleen DNE 21+ en IMAGE expliciet een model van de cementindustrie, terwijl twee modellen (Imaclim-R en MESSAGE) geen representatie hebben van de cementindustrie of de sector niet-metaalhoudende mineralen. Ook is gebleken dat in de modellen met een vertegenwoordiging van de cementindustrie twee sectorspecifieke broeikasgasreductiemaatregelen vaak niet expliciet worden meegenomen, namelijk: i) aanpassing achteraf en ii) reductie van de verhouding klinker/cement. Er is gebleken dat het inbouwen van energie-efficiëntietechnologieën in oudere installaties een extra besparing kan opleveren van 853 $MtCO_2$ in een referentiescenario en ongeveer 920 $MtCO_2$ in een mitigatiescenario in de periode 2010-2040 (ongeveer 4 en 5% van de totale CO_2-uitstoot in deze periode). Alle in aanmerking genomen aanpassingsmaatregelen werden aangemerkt als "kosteneffectief" (d.w.z. het kost minder om de energie-efficiëntiemaatregel te nemen dan niet) of anders bekend als "low-regret"-maatregelen, maatregelen die doorgaans door energiemodellen worden genegeerd. De koppeling van de beschikbaarheid van hoogovenslakken en vliegas (d.w.z. de belangrijkste klinkersupplementen) aan het potentieel van klinker-cementreductie beïnvloedt de modelresultaten aanzienlijk. Berekend is dat indien alle beschikbare supplementaire materialen worden gebruikt, met inachtneming van de productbeperkingen, de energievraag voor cementproductie in 2100 15% lager is dan oorspronkelijk geraamd in een referentiescenario. In een mitigatiescenario zal, omdat veel kolengestookte elektriciteitscentrales volgens het model zullen sluiten, de toekomstige beschikbaarheid van vliegas beperkt zijn en daarmee ook het potentieel voor energiebesparingen door vervanging van klinker in de cementindustrie. De beperkte beschikbaarheid van vliegas kan de noodzaak doen ontstaan om historische "voorraden" vliegas, bijvoorbeeld vliegasbassins bij elektriciteitscentrales, te ontginnen en andere klinkervervangende materialen, zoals BF-slak, die momenteel slechts gedeeltelijk worden benut, beter te benutten (een groot deel van BF is luchtgedroogd, zodat het potentieel ervan in de cementindustrie niet volledig wordt benut). In dit scenario blijken de energievraag en de broeikasgasemissies in 2100 14% hoger te liggen dan geraamd wanneer geen rekening wordt gehouden met de gevolgen die beleidsmaatregelen in de energiesector kunnen hebben voor de cementindustrie. Voor een volledige modellering van de onderlinge relaties tussen sectoren (en dus een nauwkeurige modellering van het potentieel) en een volledige weergave van het potentieel voor energie-efficiëntie (ook in de vorm van aanpassingen achteraf) is een meer gedetailleerde modellering van de industrieën in langetermijnenergiemodellen vereist.

In hoofdstuk 6 wordt nagegaan hoe een andere belangrijke, in termen van energie en broeikasgasemissies, industriële sector; de staalindustrie, in langetermijnenergiemodellen is vertegenwoordigd. De staalindustrie werd gekozen omdat zij verantwoordelijk is voor ongeveer een kwart van de industriële energievraag en de directe industriële CO_2-emissies. Van de twaalf beoordeelde modellen blijken er slechts zeven een vertegenwoordiging van de staalsector te hebben, terwijl slechts vijf modellen de fysieke vraag (in ton product) modelleren. Voor het maken van prognoses van de industriële activiteit wordt in energiemodellen voor de lange termijn de jaarlijkse vraag naar staal gewoonlijk gekoppeld aan de ontwikkelingen van het bruto binnenlands product (BBP). Uit de literatuur blijkt echter dat de staalvoorraden in gebruik, en niet het jaarlijkse staalverbruik, een betere indicator voor de vraag naar staal vormen. In hoofdstuk 6 wordt daarom geëvalueerd hoe een andere benadering van de raming van de toekomstige vraag, die gebaseerd is op de accumulatie van de staalvoorraden in het verleden, de modelresultaten kan beïnvloeden. Gebleken is dat met beide benaderingen (een "flow-based"-benadering die het jaarlijkse staalverbruik koppelt aan het BBP en een "stock-based"-benadering die de staalvoorraden in gebruik koppelt aan het BBP) de mondiale vraag naar staal in de eerste helft van de 21e eeuw in een vergelijkbaar tempo toeneemt. Wat de tweede helft van de eeuw betreft, blijken de prognoses van de twee benaderingen echter sterk uiteen te lopen. Bij de op stromen gebaseerde benadering blijft de vraag naar staal toenemen, zij het minder drastisch, tot 2.600 Mton/jaar in 2100, terwijl bij de op voorraden gebaseerde benadering de vraag naar staal 75% lager wordt geraamd op 1.600 Mton/jaar. In de tweede helft van de eeuw blijken de staalvoorraden in gebruik het verzadigingsniveau te hebben bereikt en niet verder toe te nemen, hetgeen betekent dat aan de gehele vraag naar staal kan worden voldaan met staal dat de geaccumuleerde staalvoorraden verlaat (gepensioneerd staal). Aangezien de staalproductie een grote bijdrage levert aan de broeikasgasemissies, betekent dit dat de IAM's momenteel de industriële emissies in de laatste helft van de eeuw en daarmee de investeringen die nodig zijn voor de beperking van broeikasgassen, mogelijk overschatten.

8.4 Algemene conclusies

Tot slot keren wij terug naar de belangrijkste onderzoeksvraag:

In welke mate kan een verbetering van de energie-efficiëntie de industriële energievraag doen afnemen en zijn de belangrijkste kenmerken van de industrie en de mitigatiemaatregelen voldoende opgenomen in de energiemodellen op lange termijn?

Geschat wordt dat, ondanks de historische verbeteringen van de energie-efficiëntie en de toegenomen inspanningen op het gebied van recycling, de toepassing van energie-efficiënte technologieën/maatregelen en hoge recyclingpercentages de wereldwijde industriële energievraag op korte termijn met een kwart kunnen doen afnemen: van 185 EJ tot 140 EJ in 2050. Het grootste energiebesparingspotentieel wordt geïdentificeerd voor niet-OESO-landen, die verantwoordelijk blijken te zijn voor het grootste deel van de toekomstige vraag naar industriële energie, terwijl het merendeel van de energiebesparingen kan worden bereikt in de andere sector, die de minder energie-intensieve industrieën omvat (bv. machines, textiel, voedingsmiddelen en tabak). De primaire aluminiumindustrie, een zeer energie-intensieve bedrijfstak die sterk afhankelijk is van elektriciteit, die het grootste deel van de productiekosten uitmaakt, is er in de afgelopen jaren in geslaagd haar energie-efficiëntiepotentieel aanzienlijk te benutten. Als dezelfde energie-efficiëntietrends aanhouden, zal er tegen 2050 naar schatting bijna geen ruimte meer zijn voor verbetering van de energie-efficiëntie in de aluminiumsmelterijen. Anderzijds is de tussenstap bij de productie van aluminium, de minder energie-intensieve en van fossiele brandstoffen afhankelijke productie van aluminiumoxide, nog verder verwijderd van de verwezenlijking van het technische energiebesparingspotentieel. Er wordt vastgesteld dat het toekomstige energiebesparingspotentieel, als de huidige trends inzake energie-efficiëntie aanhouden, daalt tot 12% voor de raffinage van aluminiumoxide en tot 0,9% voor het smelten van aluminium.

Om het vastgestelde energiebesparingspotentieel van 44 EJ te verwezenlijken, moeten alle belemmeringen, bijvoorbeeld op economisch, technologisch of kennisgebied, en op organisatorisch gebied, worden overwonnen. Bovendien moeten de minder energie-intensieve, maar niet goed onderzochte industrieën, bijvoorbeeld de aluminiumoxideraffinage, ook alle energie-efficiëntiemogelijkheden op grote schaal implementeren. Ten slotte blijkt dat, hoewel het energiebesparingspotentieel aanzienlijk is, dit niet volstaat om de EU-doelstellingen voor 2050 te bereiken, wat onderstreept dat er meer maatregelen, zoals koolstofarme technologieën en materiaalefficiëntie, moeten worden genomen.

Na een evaluatie van het effect van verbeteringen van de energie-efficiëntie op de toekomstige vraag naar industriële energie, werd met dit onderzoek beoogd na te gaan of in energiemodellen op lange termijn rekening wordt gehouden met specifieke kenmerken van de industrie, en bijgevolg of het in deze modellen vastgestelde potentieel voor energie-efficiëntie voldoende wordt weergegeven. Energiemodellen hebben een reeks meervoudige koppelingen tussen verschillende systemen met het oog op het vastleggen en evalueren van beleidsmaatregelen inzake klimaatverandering. Gebleken is dat industriële details slechts in sommige modellen zijn opgenomen, terwijl veel modellen de industriële sector als geheel weergeven, zonder rekening te houden met industriële details. De grote verschillen tussen de modellen kunnen gedeeltelijk de eveneens grote verschillen verklaren die bij onderlinge vergelijking van modellen zijn vastgesteld (16 Gt/jaar verschil in emissies bij eenzelfde scenario), waarbij modellen met minder industriële details een grotere flexibiliteit mogelijk maken bij het onderzoek naar bijvoorbeeld elektrificatie. Er zijn belangrijke onzekerheden voor alle modellen, zoals de verzadiging van de vraag naar verschillende industriële goederen in de verschillende regio's, of de penetratiegraad van nieuwe technologieën, of technologievoorkeuren, maar basisverbanden, b.v. tussen industriële activiteit en energie-intensiteit, zijn goed mogelijk. Er is dus nog veel ruimte om de modelprognoses te verbeteren door kennis op belangrijke gebieden toe te voegen via bottom-up analyse.

Dit geldt zelfs voor de modellen die reeds een expliciete vertegenwoordiging van de industriële subsector hebben. Door de retrofit van oudere fabrieken met energie-efficiënte technologieën op te nemen als koolstofbeperkende maatregel in de cementindustrie, bleek dat tussen 2010-2040 op kosteneffectieve wijze een niet-significante hoeveelheid CO_2-emissies kan worden bespaard, een maatregel die voorheen door de modellen werd genegeerd. Bovendien kan beleid in een bepaalde sector het CO_2-verminderingspotentieel in een andere sector beïnvloeden. In een scenario waarin de energiesector kolengestookte elektriciteitscentrales uitschakelt, zal bijvoorbeeld de productie van waardevolle bijproducten voor andere industrieën worden beperkt. Een dergelijk bijproduct is vliegas, dat door de cementindustrie kan worden gebruikt om de koolstofemissies te verminderen. Door deze intersectorale relatie in het model op te nemen, werd een eerder vastgesteld energiebesparingspotentieel van ongeveer 14% door een groter gebruik van vliegas geëlimineerd.

Energiemodellen voor de lange termijn kunnen ook baat hebben bij studies die de materiaalcycli in detail beoordelen en de manier waarop zij prognoses van de materiaalvraag maken, verbeteren. Door de resultaten van de materiaalstroomanalyse (MFA) inzake de ontwikkeling van de staalvoorraden te gebruiken en deze te koppelen aan prognoses van de vraag naar staal, is een aanzienlijk andere ontwikkeling van de vraag aan het licht gekomen, met name na 2050, waarbij de vraag naar staal na een bepaalde waarde aanzienlijk afneemt. Het gebruik van een andere en betere vraagindicator resulteerde in een 75% lagere vraagprognose tegen 2100, wat gevolgen heeft voor alle modelresultaten, zoals prognoses voor de energievraag, prognoses voor broeikasgassen, mitigatiepotentieel per technologie, vereiste investeringen en andere systeemeffecten. Ten slotte moet, om de resultaten van de industriële modellering in energiemodellen op lange termijn te verbeteren, (1) gebruik worden gemaakt van belangrijke sectorspecifieke informatie uit bottom-up studies, (2) moeten de belangrijkste interrelaties tussen sectoren worden geïdentificeerd en (3) kunnen de resultaten van materiaalcyclusanalyses worden gebruikt om betere vraagindicatoren af te leiden.

9 References

Chapter 1

Ackerman, F., S.J. DeCanio, R.B. Howarth, and K. Sheeran. Limitations of Integrated Assessment Models of climate change. *Climatic Change*, 95, p. 297-315.

Allwood, J.M., M.F. Ashby, T.G. Gutowski, and E. Worrell. (2011). Material efficiency: A white paper. Resources, Conservation and Recycling, 55, p. 362-381.

Allwood, J.M., J.M. Cullen, and R.L. Milford. (2010). Options for achieving a 50% cut in industrial carbon emissions by 2050. *Environ. Sci. Technol.*, 44, p.1888-1894.

Bühler, F. A. Guminski, A. Gruber, S. von Roon, and B. Elmegaard. (2017). Energy saving potential, costs and uncertainties in the industry: A case study of the chemical industry in Germany. Proceedings of the ECOS 2017 – the 30th international conference on efficiency, cost, optimization, simulations and environmental impact of energy systems. July 2-6, 2017, San Diego, California, the United States.

Calvin, K., L. Clarke, V. Krey, G. Blanford, K. Jiang, M. Kainuma, E. Kriegler, G. Luderer and P.R. Shukla. (2012). The role of Asia in mitigating climate change: results from the Asia modeling exercise. *Energy Economics* (34), p. S251-S260.

Calvin, K., M. Wise, D. Klein, D. McCollum, M. Tavoni, B. van der Zwaan, and D.P. van Vuuren. (2013). A multi-model analysis of the regional and sectoral roles of bioenergy in near-and long-term CO 2 emissions reduction. *Climate Change Economics*, **4**(04): p. 1340014.

Clarke L., K. Jiang, K. Akimoto, M. Babiker, G. Blanford, K. Fisher-Vanden, J.-C. Hourcade, V. Krey, E. Kriegler, A. Löschel, D. McCollum, S. Paltsev, S. Rose, P.R. Shukla, M. Tavoni, B.C.C. van der Zwaan, and D.P. van Vuuren, (2014). Assessing Transformation Pathways. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Global Cement and Concrete Association (GCCA). (2020). GNR project reporting CO_2. London, United Kingdom. https://gccassociation.org/gnr/

Central Committee of the Communist Party of China (CCCPC). (2015). The 13th five-year plan for economic and social development of the people's republic of China (2016-2020).

Corsten, M. (2009). Global CO_2 abatement potential in the iron and steel industry up to 2030. M.Sc. thesis, August 2009. NWS-S-2009-25. Utrecht University, Utrecht, the Netherlands.

Crompton, P. (2000). Future trends in Japanese steel consumption. *Resources Policy* (26), 103-114.

de Vries H.J.M., D. P. van Vuuren, M.G.J. den Elzen, and M.A. Janssen. (2001). *The Targets Image Energy Regional (TIMER) Model - Technical documentation*. Report 461502024/2001. Department of International Environmental Assessment, National Institute of Public Health and the Environment (RIVM), Bilthoven, the Netherlands.

de Vries, H.J.M., K. Blok, M.K. Patel, M. Weiss, S. Joosen, E. de Visser and J. Sijm. (2006). Assessment of the interaction between economic and physical growth. EPIST project report UCE-34. Prepared by the Netherlands Research Programme on Scientific Assessment and Policy Analysis for Climate Change. University of Utrecht, the Netherlands.

European Commission JRC-IPTS. (2010). IPPC Reference Document on Best Available Techniques (BREF) in the Cement, Lime and Magnesium Oxide Manufacturing Industries, May 2010. http://eippcb.jrc.ec.europa.eu/reference/

European Union (EU). (2011). A Roadmap for moving to a competitive low carbon economy in 2050. European Commission, Brussels, Belgium.

European Commission (EC). (2019). Clean energy for all Europeans. European Commission, Brussels, Belgium. https://ec.europa.eu/energy/topics/energy-strategy/clean-energy-all-europeans_en

European Commission (EC). (2020b). Stepping up Europe's climate ambition. European Commission, Brussels, Belgium. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0562

European Commission (EC). (2020a). 2030 Climate Target Plan Impact Assessment. Stepping up Europe's 2030 climate ambition. European Commission, Brussels, Belgium. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020SC0176

European Commission (EC). (2018b). Directive (EU) 2018/2002 of the European Parliament and of the Council of 11 December 2018 amending Directive 2012/27/EU on energy efficiency. European Commission, Brussels, Belgium. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2018.328.01.0210.01.ENG

European Commission (EC). (2018a). A Clean Planet for all A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy. European Commission, Brussels, Belgium. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52018DC0773

FAOSTAT (2020a). Paper production (including newsprint, printing and writing paper, other paper and paperboard). Food and Agriculture Organization of the United Nations, Rome, Italy. http://www.fao.org/home/en

FAOSTAT (2020b). Wood production (including fibreboard, particle board, plywood, coniferous sawnwood, non-coniferous sawnwood, veneer sheets). Food and Agriculture Organization of the United Nations, Rome, Italy. http://www.fao.org/home/en

Fischedick M., J. Roy, A. Abdel-Aziz, A. Acquaye, J.M. Allwood, J.-P. Ceron, Y. Geng, H. Kheshgi, A. Lanza, D. Perczyk, L. Price, E. Santalla, C. Sheinbaum, and K. Tanaka (2014). Industry. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Gale, J. & Freund, P. (2001). Greenhouse gas abatement in energy intensive industries. In R.A. Durie, P. McMullan, C.A.J. Paulson, A.Y. Smith and D.J. Williams (Eds.). Proceedings of the 5th

International Conference on Greenhouse Gas Control Technologies (pp. 1211-1216). Collingwood, Australia, CISRO.

Global Energy Assessment (GEA) – Toward a Sustainable Future. (2012). Cambridge University press, Cambridge UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Luxemburg, Austria.

Green, J.A.S. (2007). Aluminum recycling and processing for energy conservation and sustainability. Materials Park, Ohio: ASM International.

Graus, W., Blomen, E., & Worrell, E. (2011). Global energy efficiency improvement in the long term: a demand- and supply-side perspective. *Energy Efficiency,* 4, 435-463.

Gielen D., and Taylor, M. (2007). Modelling industrial energy use: the IEAs energy technology perspectives. *Energy Economics*, 29 (4), p. 889-912.

Girod, B., D.P. van Vuuren, M. Grahn, A. Kitous, S.H. Kim, and P. Kyle. (2013). Climate impact of transportation - A model comparison. *Climatic Change*, **118**(3-4): p. 595-608.

Griffin, P.W., G.P. Hammond, J. B. Norman. (2017). Industrial energy use and carbon emissions reduction in the chemicals sector: A UK perspective. Article in Press. *Applied Energy*.

Hidalgo, I., L. Szabo, J.C. Ciscar, and A. Soria. 2005. Technological prospects and CO_2 emission trading analyses in the iron and steel industry: A global model. Energy (30), p. 583-610.

Intergovernmental Panel on Climate Change (IPCC). (2014a). Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

Intergovernmental Panel on Climate Change (IPCC) (2014b). Summary for policymakers. In: Climate Change 2014: Impacts,Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1-32.

Intergovernmental Panel on Climate Change (IPCC) (2006). 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T., and Tanabe K. (eds). Volume 3, Chapter 4: Industrial Process and Product Use. Published: IGES, Japan. http://www.ipccnggip.iges.or.jp/public/2006gl/vol3.html

Intergovernmental Panel on Climate Change (IPCC) (2018). Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. In Press.

International Aluminium Institute (IAI). (2020) Statistics. London, United Kingdom. http://www.world-aluminium.org/

International Energy Agency (IEA). (2007). Tracking industrial energy efficiency and CO_2 emissions. Paris, France.

International Energy Agency (IEA). (2008). Assessing measures of energy efficiency performance and their application in industry. Paris, France.

International Energy Agency (IEA). (2009). Energy technology transition for industry – Strategies for the next industrial revolution. Paris, France.

International Energy Agency (IEA). (2010). Energy technology perspectives 2010 – Pathways to clean energy system. Paris, France.

International Energy Agency (IEA). (2012). Energy technology perspectives 2012 – Pathways to clean energy system. Paris, France.

International Energy Agency (IEA). (2020a). CO_2 emissions from fuel combustion. OECD/IEA, Paris France.

International Energy Agency (IEA). (2020c). World Energy Outlook 2020. OECD/IEA, Paris, France.

International Energy Agency (IEA). (2017a). Energy efficiency indicators – Highlights 2017. Paris, France.

International Energy Agency (IEA). (2017b). Energy technology perspectives 2017 – Catalysing Energy Technology Transformations. Paris, France.

International Energy Agency (IEA). (2017c). Renewable energy for industry – From green energy to green materials and fuels. Paris, France.

International Energy Agency (IEA). (2020b). Extended energy balances on non-OECD countries 2020 edition. OECD/IEA, Paris, France.

International Institute for Applied Systems Analysis (IIASA). 2014. AR5 Scenario Database Version 1.0.2. https://tntcat.iiasa.ac.at/AR5DB/dsd?Action=htmlpage&page=about#

Keys, A., M. van Hout, and B. Daniëls. 2019. Decarbonisation options for the Dutch steel industry. PBL Netherlands, Environmental Assessment Agency and ECN part of TNO. The Hague, Netherlands.

Krey V. (2014) Global energy-climate scenarios and models: a review. *WIREs Energy Environ.* 2014, 3, p. 363-383.

Kriegler, E., J.P. Weyant, G.J. Blanford, V. Krey, L. Clarke, J. Edmonds, A. Fawcett, G. Luderer, K. Riahi, R. Richels, S.K. Rose, M. Tavoni, and D.P. van Vuuren. (2014). The role of technology for achieving climate policy objectives: overview of the EMF 27 study on global technology and climate policy strategies. *Climatic Change*, **123** (3-4): p. 353-367.

Laurijssen, J. (2013). Energy use in the paper industry – An assessment of improvement potentials at different levels. PhD thesis. Kenniscentrum Papier en Karton (KCPK), Arnhem and Utrecht University, Utrecht, Netherlands.

Luo, Z. & Soria, A. (2007). Prospective study of the world aluminium industry. JRC Scientific and Technical Reports, EUR 22951 EN-2007.

Moya J.A., A. Boulamati, S. Slingerland, R. van der Veen, M. Gancheva, K.M. Rademaekers, J.J.P. Kuenen, A.J.H. Visschedijk (2015). Energy efficiency and GHG emissions: Prospective scenarios for the aluminium industry. JRC Scientific and Technical Reports, EUR 27335 EN.

Müller, D.B., J. Cao, E. Kongar, M. Altonji, P-H. Weiner, and T.E. Graedel. 2007. Service lifetimes of mineral end uses. U.S. Geological Survey, Minerals Resources External Research Program Award Number: 06HQGR0174.

Müller, D.B., T. Wang, and B. Duval. (2011). Patterns of iron use in societal evolution. *Environ. Sci. Technol.*, 45, p. 182-188.

Neelis, M., and Patel, M. (2006). Long-term production, energy consumption and CO_2 emission scenarios for the worldwide iron and steel industry. Utrecht University, Utrecht, the Netherlands.

Pauliuk, S., T. Wang, D.B. and Müller. (2013). Steel all over the world: Estimating in-use stocks of iron for 200 countries. *Resources, Conservation and Recycling*, 71, p. 22-30.

Pauliuk, S., A. Arvesen, K. Stadler, E.G. Hertwich. (2017). Industrial ecology in integrated assessment models. Nat. Clim. Chang., 7, p. 13–20.

Plastics Europe (2016a). Plastics – the Facts 2016 An analysis of European plastics production, demand and waste data. Association of plastics Manufacturers. Brussels, Belgium https://www.plasticseurope.org/en

Plastics Europe (2016b). World plastics production. Presentation. Association of plastics Manufacturers. Brussels, Belgium

Plastics Europe (2019). Plastics – the Facts 2019 An analysis of European plastics production, demand and waste data. Association of plastics Manufacturers. Brussels, Belgium. https://www.plasticseurope.org/en

Plastics Europe (2020). Plastics – the Facts 2020 An analysis of European plastics production, demand and waste data. Association of plastics Manufacturers. Brussels, Belgium. https://www.plasticseurope.org/enPlanbureau voor de Leefomgeving (PBL). (2014) IMAGE framework/IMAGE 3.0 in a nutshell. http://themasites.pbl.nl/models/image/index.php/IMAGE_framework/IMAGE_3.0_in_a_nutshell

Rosen, R.A. and E. Guenther. (2015). The economics of mitigating climate change: What can we know? *Technological Forecasting and Social Change*, 91: p. 93-106.

Rosen, R.A. (2015). Critical review of: "Making or breaking climate targets — the AMPERE study on staged accession scenarios for climate policy". Technological Forecasting & Social Change, 96, p. 322-326.

Ryan, L., & Campbell, L. (2012). Spreading the net: The multiple benefits of energy efficiency improvements. International Energy Agency (IEA). Paris, France.

Sathaye, J., T., Xu, and C. Galitsky. (2010). Bottom-up representation of industrial energy efficiency technologies in Integrated Assessment Models for the cement industry. Ernest Orlando Berkeley National Laboratory (LBNL). LBNL-4395E

Saygin, D., E. Worrell, M.K. Patel, and D.J. Gielen. (2011). Benchmarking the energy use of energy-intensive industries in industrialized and in developing countries. *Energy 36* (2), 6661-6673.

Stehfest, E., van Vuuren, D., Kram, T., Bouwman, L., Alkemade, R., Bakkenes, M., Biemans, H., Bouwman, A., den Elzen, M., Janse, J., Lucas, P., van Minnen, J., Müller, C., Prins, A. (2014). Integrated Assessment of Global Environmental Change with IMAGE 3.0. Model description and policy applications, The Hague: PBL Netherlands Environmental Assessment Agency. The Hague, the Netherlands

Sugiyama, M., O. Akashi, K. Wada, A. Kanudia, J. Li, and J. Weyant. (2014). Energy efficiency potentials for global climate change mitigation. *Climatic Change*, 123(3-4), p. 397-411.

United Nations Framework Convention on Climate Change (UNFCCC). (2015). Adoption of the Paris Agreement. United Nations, New York.

United States Geological Survey (USGS). (2017a). Cement. Historical statistics for mineral and material commodities in the United States: U.S. Geological Survey Data Series 140. U.S. Department of the Interior U.S. Geological Survey. https://www.usgs.gov/centers/nmic/historical-statistics-mineral-and-material-commodities-united-states

United States Geological Survey (USGS). (2017b). Nitrogen [fixed]- Ammonia. Historical statistics for mineral and material commodities in the United States: U.S. Geological Survey Data Series 140. U.S. Department of the Interior U.S. Geological Survey. https://www.usgs.gov/centers/nmic/historical-statistics-mineral-and-material-commodities-united-states

United States Geological Survey (USGS). (2017c). Zinc. Historical statistics for mineral and material commodities in the United States: U.S. Geological Survey Data Series 140. U.S. Department of the Interior U.S. Geological Survey. https://www.usgs.gov/centers/nmic/historical-statistics-mineral-and-material-commodities-united-states

United States Geological Survey (USGS). (2018a). Cement. Mineral commodity summaries January 2018. U.S. Department of the Interior U.S. Geological Survey.

United States Geological Survey (USGS). (2018b). Nitrogen [fixed]- Ammonia. Mineral commodity summaries January 2018. U.S. Department of the Interior U.S. Geological Survey.

United States Geological Survey (USGS). (2019a). Cement. Mineral commodity summaries February 2019. U.S. Department of the Interior U.S. Geological Survey.

United States Geological Survey (USGS). (2019b). Nitrogen [fixed]- Ammonia. Mineral commodity summaries February 2019. U.S. Department of the Interior U.S. Geological Survey.

United States Geological Survey (USGS). (2020a). Cement. Mineral commodity summaries January 2020. U.S. Department of the Interior U.S. Geological Survey.

United States Geological Survey (USGS). (2020b). Nitrogen [fixed]- Ammonia. Mineral commodity summaries January 2020. U.S. Department of the Interior U.S. Geological Survey.

United States Geological Survey (USGS). (2020c). 2017 Minerals yearbook. Zinc [advance release]. U.S. Department of the Interior U.S. Geological Survey.

United States Geological Survey (USGS). (2018). Mineral Commodity Summaries - Cement, January 2016. U.S. Department of the Interior U.S. Geological Survey.

van der Zwaan, B.C.C., H. Rösler, T. Kober, T. Aboumahboub, K.V. Calvin, D.E.H.J. Gernaat, G. Marangoni, and D. McCollum. (2013) A cross-model comparison of global long-term technology diffusion under a 2 C climate change control target. *Climate Change Economics*, 2013. **4**(04): p. 1340013.

van Ruijven, B. J., D. P. Van Vuuren, W. Boskaljon, M. L. Neelis, D. Saygin; M. K. Patel. (2016). Long-term model-based projections of energy use and CO_2 emissions from the global steel and cement industries. Resources, Conservation and Recycling, volume 112, pp. 15 – 36.

Van Vuuren, D.P., B.J., Strengers, and H.J.M. De Vries. (1999). Long-term perspectives on world metal use—a system dynamics model. Resources Policy 25, 239–255

van Vuuren D.P., B.J. Strengers, and H.J.M de Vries. (1999). Long-term perspectives on world metal use - a system-dynamics model. *Resource Policy* (25), 239-255.

Weyant, J. (2017). Some contributions of Integrated Assessment Models of global climate change. *Review of Environmental Economics and Policy* (11), p. 115-137.

World Meteorological Organization (WMO). (2020). United in Science 2020. https://public.wmo.int/en/resources/united_in_science

World Resources Institute (WRI). (2021). Historical greenhouse gas emissions. https://www.climatewatchdata.org/ghg-emissions?source=CAIT

World Steel Association. (1978-2020). Steel statistical yearbooks. Steel statistics archive. Brussels, Belgium. https://www.worldsteel.org/steel-by-topic/statistics/steel-statistical-yearbook.html

World Steel Association. (2017b). Steel statistical yearbook 2017. Brussels, Belgium.

World Steel Association. (2020). Steel statistical yearbook 2020. Brussels, Belgium.

World Steel Association. (2010). Steel statistical yearbook 2010. Brussels, Belgium.

World Steel Association. (2017a). Steel' s contribution to a low carbon future and climate resilient societies. Brussels, Belgium.

Worrell, E., J. Allwood, and T. Gutowski. (2016). The role of material efficiency in environmental stewardship. *Annu. Rev. Resour.*, 41, p. 575-598.

Worrell, E., L. Bernstein, J. Roy, L. Price, and J. Harnisch. (2009). Industrial energy efficiency and climate change mitigation. *Energy Efficiency*, 2, p. 109-123.

Worrell, E. and Carreon J.R. (2017). Energy demand for materials in an international context. Phil. Trans. R. Soc. A375: 20160377. http://dx.doi.org/10.1098/rsta.2016.0377

Xu, T., J. Sathaye, and C. Galitsky. (2010). Development of bottom-up representation of industrial energy efficiency technologies in integrated assessment models for the iron and steel sector. Ernest Orlando Berkeley National Laboratory.

Yellishetty, M., and G.M. Mudd. (2014). Substance flow analysis of steel and long term sustainability of iron ore resources in Australia, Brazil, China and India. *Journal of Cleaner Production*, 84, p. 400-410.

Zhang, S., E. Worrell, and W. Crijns-Graus. (2015). Synergy of air pollutants and greenhouse gas emissions of Chinese industries: A critical assessment of energy models. *Energy*, **93**: p. 2436-2450.

Zhou, N., D. Fridley, M. McNeil, N. Zheng, J. Ke, and M. Levine. (2011). China's Energy and Carbon Emissions Outlook to 2050. Ernest Orlando Berkeley National Laboratory.

Zhou, S., G.P. Kyle, S. Yu, L.E. Clarke, J. Eom, P. Luckow, V. Chaturvedi, X. Zhang, and J.A. Edmonds. (2013). Energy use and CO2 emissions of China's industrial sector from a global perspective. *Energy Policy* (58), p. 284–294.

Chapter 2

Bureau of International Recycling (BIR) (2012). World steel recycling in figures 2007 – 2011: Steel scrap – a raw material for steel making. http://www.bir.org/assets/Documents/publications/brochures/WorldSteelinFiguresIIIFINLoRes.pdf. Accessed 10 July 2013.

Confederation of European Paper Industries (CEPI) (2006). Europe global champion in paper recycling: paper industries meet ambitious target. http://www.cepi.org/system/files/public/documents/pressreleases/recycling/2006/PRRECYCLING.pdf. Accessed 10 July 2013.

Confederation of European Paper Industries (CEPI) (2011). CEPI sustainability report 2011. http://www.cepi-sustainability.eu/uploads/Sustainability_Report_WEB.pdf. Accessed 10 July 2013.

De Beer, J. (1998). Potential for industrial energy-efficiency improvement in the long term. PhD thesis, Utrecht University, Utrecht, the Netherlands.

De Beer, J., Worrell E., & Blok, K. (1998). Future technologies for energy-efficient iron and steel making. *Annu. Rev. Energy Environ.,* 23, 123-205.

Energy Information Administration (EIA) 1999. Model documentation report: Industrial sector demand module of the national energy modeling system. Energy Information Administration, U.S. Department of Energy, Washington, D.C.

Eurofer (2011). 2007-2011 European steel in Figures. http://www.eurofer.org/eurofer/Publications/pdf/2011-ESF.pdf. Accessed 6 May 2013.

European Aluminium Association (EAA) (2010). Sustainability of the European aluminium industry 2010. http://www.alueurope.eu/pdf/2010%20Sustainability%20of%20the%20European%20aluminium%20industry.pdf. Accessed 15 August 2013.

European Integrated Pollution Prevention and Control Bureau (EIPPCB) (2013). Best Available Techniques (BAT) reference document for iron and steel production. http://eippcb.jrc.ec.europa.eu/reference/. Accessed 8 July 2013.

European Integrated Pollution Prevention and Control Bureau (EIPPCB) (2010). Reference document on Best Available Techniques in the cement, lime and magnesium oxide manufacturing industries. http://eippcb.jrc.ec.europa.eu/reference/BREF/clm_bref_0510.pdf. Accessed 10 May 2013.

Fleiter, T., Schlomann, B., & Eichhammer, W. (2013). Energieverbrauch und CO_2-Emissionen industrieller Prozesstechnologien - Einsparpotenziale, Hemmnisse und Instrumente, Stuttgart, Germany.

Food and Agriculture Organization Statistics (FAOSTAT) (2013). Forestry statistics. http://faostat.fao.org/site/626/DesktopDefault.aspx?PageID=626#ancor. Accessed 29 November 2013.

Fruehan, R.J., Fortini, O., Paxton H.W., & Brindle R. (2000). Theoretical minimum energies to produce steel for selected conditions. Carnegie Mellon University, Pittsburgh, United States.

Global Aluminium Recycling Committee (GARC) (2009). Global aluminium recycling: A cornerstone of sustainable development. http://www.world-aluminium.org/cache/fl0000181.pdf. Accessed 15 August 2013.

Graus, W., Blomen, E., & Worrell, E. (2011). Global energy efficiency improvement in the long term: a demand- and supply-side perspective. *Energy Efficiency,* 4, 435-463.

Graus W., & Kermeli K. (2012). Energy demand projections for energy [R]evolution 2012. Utrecht University, commissioned by Greenpeace International and DLR.

Graus, W., & Worrell, E. (2011). Methods for calculating CO_2 intensity of power generation and consumption: A global perspective. *Energy Policy* 39, 613-627.

Green, J.A.S. (2007). Aluminum recycling and processing for energy conservation and sustainability. Materials Park, Ohio: ASM International.

Gu, S., & Wu, J. (2012). Review on the energy saving technologies applied in Bayer process in China. Proceeding of the 9th International alumina quality workshop 2012, Perth, Australia, 379-384.

Hekkert, M.P., Joosten L.A.J., & Worrell, E. (1998). Material efficiency improvement for European packaging in the period 2000-2020. In Factor 2 / Factor 10, Utrecht.

Henrickson, L. (2010). The need for energy efficiency in Bayer refining. *Proceedings of TMS Annual Meeting – Light Metals*, 173-178.

International Aluminium Institute (IAI) 2013a. 2010 Life cycle inventory data for the worldwide primary aluminium industry. http://www.world-aluminium.org/. Accessed 02 September 2023.

International Aluminium Institute (IAI) 2013b. Current IAI statistics. http://www.world-aluminium.org/Statistics. Accessed 15 May 2013.

International Energy Agency (IEA) (2004). Energy statistics manual. Paris, France.

International Energy Agency (IEA) (2007). Tracking industrial energy efficiency and CO_2 emissions. Paris, France.

International Energy Agency (IEA) (2008). Energy technology perspectives 2008 – Scenarios and strategies to 2050. Paris, France.

International Energy Agency (IEA) (2009a). Energy technology transitions for industry: Strategies for the next industrial revolution. Paris, France.

International Energy Agency (IEA) (2009b). Chemical and petrochemical sector: Potential of best practice technology and other measures for improving energy efficiency. IEA Information Paper. Paris, France.

International Energy Agency (IEA) (2011a). Energy Balances 2011 edition with 2009 data. Paris, France.

International Energy Agency (IEA) (2011b). Key world energy statistics - 2011. Paris, France.

International Energy Agency (IEA) (2011c). World Energy Outlook 2011 edition. Paris, France.

International Energy Agency (IEA) (2012). Energy technology perspectives 2012 - pathways to a clean energy system. Paris, France.

International Energy Agency - World Business Council for Sustainable Development (IEA-WBCSD) (2009). Cement technology roadmap 2009 - Carbon emissions reductions up to 2050. http://www.iea.org/publications/freepublications/publication/Cement.pdf. Accessed 10 May 2013.

Kermeli, K., Worrell, E., & Masanet, E. (2011). Energy efficiency improvement and cost saving opportunities for the concrete industry. Lawrence Berkeley National Laboratory (LBNL). Berkeley, United States.

Lempert, R.J., Popper, S.W., Resetar, S.A., & Hart, S.L. (2002). Capital cycles and the timing of climate change policy. Pew center on global climate change, Washington, D.C.

Li, W., Liu, J., Liu, Z., & Wang, Y. (2008). The most important sustainable development issues of Chinese alumina industry. *Light Metals*, 191-195.

Linhoff March (2000). The methodology and benefits of total site pinch analysis. Linhoff March Energy Services.

Milford, R.L., Allwood, J.M., & Cullen, J.M. (2011). Assessing the potential of yield improvements, through process scrap reduction, for energy and CO_2 abatement in the steel and aluminium sectors. *Resources, Conservation and Recycling*, 55, 1185-1195.

Nadel, S. (2012). The rebound effect: Large or small? American Council for an Energy-Efficient Economy (ACEEE). Washington, United States.

Neelis, M., & Patel, M. (2006). Long-term production, energy consumption and CO_2 emission scenarios for the worldwide iron and steel industry. Utrecht University.

Overgaag, M., Harmsen, R., & Schmitz, A. (2009). Sectoral Emission Reduction Potentials and Economic Costs for Climate Change (SERPEC-CC), Industry & refineries sector. http://www.ecofys.com/files/files/serpec_executive_summary.pdf. Accessed 17 May 2013.

Pardo, N., Moya, J.A., & Vatoppoulos, K. (2012). Prospective scenarios on energy efficiency and CO_2 emissions in the EU iron & steel industry. JRC scientific and policy reports. Luxembourg.

Phylipsen, G.J.M. (2000). International comparisons & national commitments, analysing energy and technology differences in the climate debate. PhD thesis. Utrecht University. Utrecht, the Netherlands.

Ryan, L., & Campbell, L. (2012). Spreading the net: The multiple benefits of energy efficiency improvements. International Energy Agency (IEA). Paris, France.

Saunders, H. (2013). Is what we think of as “rebound” really just income effects in disguise? *Energy Policy*, 57, 308-317.

Saygin, D., Worrell, E., Patel, M.K., & Gielen, D.J. (2011a). Benchmarking the energy use of energy-intensive industries in industrialized and in developing countries, *Energy*, 36, 6661-6673.

Saygin, D., Patel, M.K., Worrell, E., Tam, C. & Gielen, D.J. (2011b). Potential of best practice technology to improve energy efficiency in the global chemical and petrochemical sector, *Energy*, 36, 5779-5790.

Saygin, D., Patel, M.K., and Gielen, D.J. (2010). Global industrial energy efficiency benchmarking – An energy policy tool. Working paper. Vienna, Austria.

Sinton, J.E., Lewis, J.I., Price, L.K, & Worrell, E. (2002). China’s sustainable energy future scenarios and carbon emissions analysis. Sub-report 11: international trends in energy efficiency technologies and policies. Lawrence Berkeley National Laboratory (LBNL). Berkeley, United States.

Smith, P. (2009). The processing of high silica bauxites – Review of existing and potential processes. *Hydrometallurgy*, 98, 162-176

Sorrell, S., Dimitropoulos, J., & Sommerville, M. (2009). Empirical estimates of the rebound effect: A review. *Energy Policy*, 37, 1356-1371.

Staudt, J. (2009). Memorandum to Ravi Srivastava, Samudra Vijay, and Elineth Torres. Costs and performance of controls – revised from comments. Andover Technology Partners.

Trudeau, N., Tam, C., Craczyk, D., & Taylor, P. (2011). Energy transition for industry: India and the global context. IEA Information Paper. Paris, France.

UBA (2010). Role and potential of renewable energy and energy efficiency for global energy supply. By DLR / Ecofys / Wuppertal Institute. Commissioned by Ministry of Environment, Germany.

United States Department of Energy, Energy Efficiency and Renewable Energy (U.S. DOE-EERE) (2007). U.S. energy requirements for aluminium production, historical perspective, theoretical limits and current practices. http://www1.eere.energy.gov/manufacturing/resources/aluminum/pdfs/al_theoretical.pdf. Accessed August 5 2013.

United States Geological Survey (USGS) (2002). 2002 Minerals Yearbook – Cement [advance release]. Reston, United States.

United States Geological Survey (USGS) (2007). 2005 Minerals Yearbook – Cement [advance release]. Reston, United States.

United States Geological Survey (USGS) (2011a). 2010 Minerals Yearbook – Aluminum [advance release]. Reston, United States.

United States Geological Survey (USGS) (2011b). 2010 Minerals Yearbook – Bauxite and Alumina [advance release]. Reston, United States.

United States Geological Survey (USGS) (2012). 2010 Minerals Yearbook – Cement [advance release]. Reston, United States.

Waide P., & Brunner, C.U. (2011). Energy-efficiency policy opportunities for electric motor-driven systems. International Energy Agency (IEA), working paper. Paris, France.

Wei, T. (2010). A general equilibrium view of global rebound effects. *Energy Economics*, 32 (3), 661-672.

Wischnewski R., de Azevedo Jr., C.M., Jr., Moraes E.L.S., & Monteiro, A.B. (2011). ALUNORTE global energy efficiency. *Light Metals 2011*, 179-184.

World Business Council for Sustainable Development/Cement Sustainability Initiative (WBCSD/CSI) (2012). Global cement database on CO_2 and energy information. http://wbcsdcement.org/GNR-2010/index.html. Accessed 17 May 2013.

World Business Council for Sustainable Development/Cement Sustainability Initiative-European Cement Research Academy (WBCSD/CSI-ECRA) (2009). Development of state of the art-techniques in cement manufacturing: Trying to look ahead. Dusseldorf, Geneva.

World Bank (2013). World Development Indicators (WDI) 2009. World Bank, Washington, US.

World Steel Association (Worldsteel) (2000). Steel statistical yearbook 2000. http://www.worldsteel.org/statistics/statistics-archive/yearbook-archive.html

World Steel Association (Worldsteel) (2011). Steel statistical yearbook 2011. http://www.worldsteel.org/statistics/statistics-archive/yearbook-archive.html

Worrell, E., Faaij, A.P.C, Phylipsen G.J.M., & Blok, K. (1995). An approach for analysing the potential for material efficiency improvement. *Resources, Conservation and Recycling*, 13, 215-232.

Worrell, E., Martin, N., & Price, L. (1999). Energy efficiency and carbon dioxide emissions reduction opportunities in the U.S. iron and steel sector. Lawrence Berkeley National Laboratory (LBNL). Berkeley, United States.

Worrell, E., & Biermans, G. (2005). Move over! Stock turnover, retrofit and industrial energy efficiency. *Energy Policy*, 33 (7), 949-962.

Worrell, E., & Galitsky, C. (2008). Energy efficiency improvement and cost saving opportunities for cement making. Lawrence Berkeley National Laboratory (LBNL). Berkeley, United States.

Worrell, E., Galitsky, C., Masanet, E., & Graus, W. (2008a). Energy efficiency improvement and cost saving opportunities for the glass industry. Lawrence Berkeley National Laboratory (LBNL). Berkeley, United States.

Worrell, E., Price, L., Neelis, M., Galitsky, C., & Nan, Z. (2008b). World best practice energy intensity values for selected industrial sectors. Lawrence Berkeley National Laboratory (LBNL). Berkeley, United States.

Worrell, E., Angelini, T., & Masanet, E. (2010). Managing your energy. Lawrence Berkeley National Laboratory (LBNL). Berkeley, United States.

Worrell, E., Kermeli, K., & Galitsky, C. (2013). Energy efficiency improvement and cost saving opportunities for cement making. United States Environmental Protection Agency (U.S. EPA). Washington DC, United States.

Xu, J.-H., Fleiter, T., Eichhammer, W., & Fan, Y. (2012). Energy consumption and CO_2 emissions in China's cement industry: A perspective from LMDI decomposition analysis. *Energy Policy*, 50, 821-832.

Chapter 3

Abeberese, A.B. (2013). Electricity cost and firm performance: Evidence from India. Department of Economics, Discussion paper. Columbia University. New York, United States.

ALCOA (2005). Environmental review and management programme – Wagerup refinery unit three. http://www.alcoa.com/australia/en/info_page/WAG_environment.asp. Accessed at 18 November 2013.

ALCOA (2007). Pinjarra alumina refinery efficiency upgrade – Air quality management plan.

Aluminium Bahrain (ALBA) (2010). GDR Prospectus. http://www.albasmelter.com/IR/Publications/Pages/default.aspx

Australian Aluminium Council (AAC) (2012). Australian Aluminium Council submission on the National Energy Savings initiative issues paper. Canberra, Australia.

Australian Aluminium Council (AAC) (2013). Australian alumina – industry description. http://aluminium.org.au/australian-alumina/australian-alumina. Accessed at 18 November 2013.

Australian Bureau of Statistics (ABS) (2010). Energy, Water and Environment Management, 2008-2009. Table 1, Mining and manufacturing businesses using electricity, natural gas and other fuels, by employment size, industry subdivision and selected industry group. Canberra, Australia.

BCS (2007) U.S. energy requirements for aluminum production: Historical perspective, theoretical limits, and current practice. Report to the DOE Industrial Technologies Program.

Bergsdal, H., Strømman, A.H., & Hertwich, E.G. (2004). The aluminium industry – environment, technology and production. Norwegian University of Science and Technology (NTNU) Rapport Nr 8/2004.

Bhushan, C. (2010). Challenge of the new balance: A study of the six most emissions intensive sectors to determine India's low carbon growth options. Centre for Science and Environment, New Delhi, India.

De Bruyn, S.M. & Opschoor, J.B. (1997). Development in the throughput-income relationship: theoretical and empirical observations. *Ecological Economics,* 20, 255-268.

Bureau of Resources and Energy Economics (BREE) (2013). Energy in Australia, May 2013. Canberra, Australia.

Canadian Industrial Energy End-use Data and Analysis Centre (CIEEDAC) (2012). Energy use and related data: Canadian aluminium industries 1990 to 2010. Simon Fraser University, Burnaby, BC, Canada.

Cleveland, C.J. & Ruth, M. (1998). Indicators of dematerialization and the materials intensity of use. *Journal of industrial ecology*, 2, 15-50.

Commonwealth Government Initiative (2000). Energy efficiency best practice in the Australian aluminium industry: Summary report. Canberra, Australia.

Covec (2009). Heavy industry energy demand. Prepared for the Ministry of Economic Development. Auckland, New Zealand.

CRU (2006). Northwest smelter operating outlook. https://www.alcoa.com/locations/usa_intalco/en/pdf/AlcoaSmelterOutlook.pdf. Accessed at 18 November 2013.

CRU (2010). The strategic impact of changing energy markets on the aluminium industry. Presentation to TMS. Seattle February 14-18. Unites States.

Dena (2010). Initiative Energie Efficienz Industry and Production. Available at: http://www.dena.de/fileadmin/user_upload/Publikationen/Stromnutzung/Dokumente/Datenblaetter_2010_englisch.pdf

Donaldson, D.J. (2011). Perspective on Bayer process energy. *Light metals 2011*, 711-715.

DUBAL (2010). Sustainability report 2008/2009 – facing the future in partnership. https://www.dubal.ae/media/105020/dub039_sustainability%20report_%20pdf%20for%20web.pdf. Accessed at 25 March 2014.

EMT-India (2004). Indian aluminium company limited works (Karnataka). http://www.emt-india.net/eca2004/award2004/Aluminium/Indian%20Aluminium%20Company%20Limited%20Belgaum.pdf. Accessed at 18 November 2013.

Empresa de Pesquisa Energética (EPE) (2013). Brazilian Energy Balance - Year 2012. Brazil.

Energy Information Administration (EIA) (2013a). Analysis briefs - Australia. http://www.eia.gov/countries/cab.cfm?fips=AS

Energy Information Administration (EIA) (2013b). International energy statistics. http://www.eia.gov/countries/data.cfm

Energy Information Administration (EIA) (2013c). 2010 Manufacturing Energy Consumption Survey (MECS).

Fleiter, T., Eichhammer, W., Hagemann, M., Wietschel, M., and Hirzel, S. (2009). Costs and potentials of energy savings in European industry – a critical assessment of the concept of conservation supply curves. Proceeding of the ECEE 2009 Summer study.

Gale, J. & Freund, P. (2001). Greenhouse gas abatement in energy intensive industries. In R.A. Durie, P. McMullan, C.A.J. Paulson, A.Y. Smith and D.J. Williams (Eds.). Proceedings of the 5th International Conference on Greenhouse Gas Control Technologies (pp. 1211-1216). Collingwood, Australia, CISRO.

Gao, F., Nie, Z., Wang, Z., Li, H., Gong, X., & Zuo, T. (2009). Greenhouse gas emissions and reduction potential of primary aluminium production in China. *Science in China Series E: Technological Sciences 52*, 2161-2166.

Graus, W. & Kermeli K. (2012). Energy demand projections for energy [R]evolution 2012. Utrecht University, commissioned by Greenpeace International and DLR.

Graus, W. & Worrell, E. (2011). Methods for calculating CO_2 intensity of power generation and consumption: A global perspective. *Energy Policy* 39 (2), 613-627.

Green, J.A.S. (2007). Aluminum recycling and processing for energy conservation and sustainability. Materials Park, Ohio: ASM International.

Grimsrud, B. & Kvinge, T. (2006). Har Aluminiumsindustrien en framtid i Norge? Fafo, Oslo, Norway.

Gu, S. & Wu J. (2012). Review on the energy saving technologies applied in Bayer process in China. Proceeding of the 9th International Alumina Quality Workshop, 18-22 March 2012, Perth, Australia, 379-384.

Gurov, A. (2003). Globalization and future production developments within the Russian and CIS aluminium industry. Presented at the 2nd International Melt Quality Workshop 16-17th October. Prague, Czech Republic.

Harnisch, J., Wing, I.S., Jacoby, H.D., & Prinn, R.G. (1998). Report #44. Primary aluminium production: Climate policy, emissions and costs. MIT Global Change Joint Program Report 44.

HATCH (2011). This is HATCH 2011 - The innovation era. http://www.hatch.ca/AR2011/pdf/2011Annual_Review_March7_LowRes.pdf

Henrickson, L. (2010). The need for energy efficiency in Bayer refining. *Light Metals 2010*, 173-178.

Hindalco (2004). Hindalco annual report 2002-2003. http://www.hindalco.com/investors/downloads/Hindalco-Annual-Report-FY03.pdf. Accessed at 18 November 2013.

Hindalco (2013). Manufacturing locations. http://www.hindalco.com/operations/manufacturing_locations.htm. Accessed at 18 November 2013.

Den Hond R., Hiralal I., & Rijkeboer A. (2007). Alumina yield in the Bayer process; past, present and prospects. *The Minerals, Metals & Materials Society 2007*, 37-42.

Hudson, L.K., Misra, C., Perrotta, A.J., Wefers, K., & Williams, F.S. (2005). Aluminum oxide. In Ullmann's Encyclopedia of Industrial Chemistry, electronic release, Wiley-VCH, Weinheim.

Industrial Assessment Center (IAC) (2013). Industrial Assessment Center Database. http://iac.rutgers.edu/database/

International Aluminium Institute (IAI) (2013a). Global life cycle inventory data for the primary aluminium industry – 2010 data. London, United Kingdom.

International Aluminium Institute (IAI) (2013b). Results of the 2012 anode effect survey. London, United Kingdom.

International Aluminium Institute (IAI) (2013c). Statistics. http://www.world-aluminium.org/statistics/. Last visited 19/02/2014.

International Aluminium Institute (IAI) (2013d). The global aluminium industry, 40 years from 1972. February 2013.

International Energy Agency (IEA) (2007). Tracking industrial energy efficiency and CO_2 emissions. Paris, France.

International Energy Agency (IEA) (2008). Key world energy statistics. Paris, France.

International Energy Agency (IEA) (2009a). Energy prices and taxes - Quarterly statistics - first quarter 2009. Paris, France.

International Energy Agency (IEA) (2009b). Energy technology Transitions for Industry – Strategies to the Next Industrial Revolution. Paris, France.

International Energy Agency (IEA) (2009c). Natural gas in China, market evolution and strategy. IEA Working paper series. Paris, France.

International Energy Agency (IEA) (2010). Natural Gas in India. IEA Working paper. Paris, France.

International Energy Agency (IEA) (2011a). Energy Balances 2011 edition with 2009 data. Paris, France.

International Energy Agency (IEA) (2011b). Integration of renewables – Status and challenges in China. IEA Working paper. Paris, France.

International Energy Agency (IEA) (2011c). World Energy Outlook 2011 edition. Paris, France.

International Energy Agency (IEA) (2012). Energy Technology Perspectives 2012 - Pathways to a Clean Energy System. International Energy Agency (IEA), Paris, France.

International Energy Agency – Energy Technology Systems Analysis Programme (IEA - ETSAP) (2012). Aluminium production. Technology Brief I10.

International Energy Agency Greenhouse Gas R&D Programme (IEA - GHG) (2000). Greenhouse Gases From Major Industrial Sources - IV The Aluminium Industry. Paris, France.

Intergovernmental Panel on Climate Change (IPCC) (1995). 1995 IPCC Second Assessment Climate Change 1995, J. J. Houghton, et al., eds. Cambridge, UK: Cambridge University Press.

Intergovernmental Panel on Climate Change (IPCC) (2006a). 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T., and Tanabe K. (eds). Volume 2, Chapter 1: Energy. Published: IGES, Japan. http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol2.html

Intergovernmental Panel on Climate Change (IPCC) (2006b). 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T., and Tanabe K. (eds). Volume 3, Chapter 4: Industrial Process and Product Use. Published: IGES, Japan. http://www.ipccnggip.iges.or.jp/public/2006gl/vol3.html

Institute for Prospective Technology Studies (IPPC) (IPTS/EC) (2013). Best Available Techniques (BAT) reference document for the non-ferrous metal industries (draft 3, February 2013). Brussels, Belgium.

Klett, C., Reeb, B., Missalla, M., & Schmidt, H.-W. (2011). Methods to reduce operating costs in circulating fluidized bed calcination. *Light Metals 2011*, 125-130.

Kunwar, R. (2011). Glimpse of most energy efficient HTD alumina refinery in the world. Available at: http://bauxite2aluminium.blogspot.nl/2012/01/industry-benchmark-of-energy.html

Laitner, J.A., Worrell, E., Galitsky, C., and Hanson, D.A. (2003). Characterizing emerging industrial technologies in energy models. Proceedings of the 2003 ACEE Summer Study on Energy Efficiency in Industry.

Li, W., Liu, J., & Liu, Z. (2008). The most important sustainable development issues of Chinese alumina industry. *Light Metals*, 191-195.

Li, W. & Yang, J. (2010). Review on sustainable development of China aluminum industry. *Travaux*, 35 no. 39, 167-172.

Liao, X. & Li, L. (2010). An optimum approach to processing medium and low grade bauxite effectively & economically. *TRAVAUX,* vol. 35, 193-199.

Liu, L., Aye, L., Lu, Z., & Zhang, P. (2006). Analysis of the overall energy intensity of alumina refinery process using unit process energy intensity and product ratio method. *Energy*, 31, 1167-1176.

Liu, Z., Men, C., & Ma, C. (2010). Global development and situation of bauxite exploitation and alumina production. *Travaux*, 35, 211-221.

Luo, Z. & Soria, A. (2007). Prospective study of the world aluminium industry. JRC Scientific and Technical Reports, EUR 22951 EN-2007.

Martin, N., Anglani, N., Einstein, D., Khrushch, M., Worrell, E., and L.K. Price. (2000). Opportunities to improve energy efficiency and reduce greenhouse gas emissions in the U.S.

pulp and paper industry. Lawrence Berkeley National Laboratory (LBNL). Berkeley, United States.

Ministerio de Minas E Energia (2012). Statistical Yearbook 2011, Brazilian metallurgical industry. Brazil.

Ministry of environment and forests, Ministry of defense (2008). Forty-sixth report - committee on petitions. New Delhi, India.

Missalla, M., Schmidt, H-W., Filhio, J.R.A., & Wischnewski, R. (2011). Significant impovement of energy efficiency at Alunorte's calcination facility. Light Metals 2011, 157-162.

Morrey, G.W. (2001). New smelter capacity required! Examining the options and costs from debottlenecking to greenfield investment. London: Hatch Associates.

National Confederation of Industry (CNI) (2012). The sustainability of Brazilian aluminum industry. http://www.abal.org.br/downloads/ing-abal-rio20.pdf. Accessed at 18 November 2013.

Neelis, M., & Patel, M. (2006). Long-term production, energy consumption and CO_2 emission scenarios for the worldwide iron and steel industry. Utrecht University.

Northern Territory Environment Protection Authority (NTEPA) (2004). Draft – Environmental impact statement_ Alcan Gove alumina refinery expansion project. http://www.ntepa.nt.gov.au/environmental-assessments/assessment/register/alcangove/draft. Accessed at 18 November 2013.

Norwegian Water Resources and Energy Directorate (NVE) (2009). Energy in Norway. http://www.nve.no/Global/Energi/Analyser/Energi%20i%20Norge%20folder/Energy%20in%20Norway%202009%20edition.pdf. Accessed at 18 November 2013.

Outotec (2011). Outotec® fluidization technology. http://www.outotec.com/

Press Information Bureau (PIB) Government of India (2003). Ministry of mines – NALCO. http://pib.nic.in/archieve/lreleng/lyr2003/rapr2003/10042003/r1004200337.html. Accessed at 18 November 2013.

Rio Tinto Alcan (2010). Gladstone sustainable development report 2010. http://www.riotintoalcan.com/. Accessed 18 November 2013.

Saygin, D., Worrell, E., Patel, M.K., & Gielen, D.J. (2011). Benchmarking the energy use of energy-intensive industries in industrialized and in developing countries, *Energy*, 36, 6661-6673.

Schwarz, H.-G. (2008). Technology diffusion in metal industries: driving forces and barriers in the German aluminium smelting. *Journal of Cleaner Production*, 216, 37-39.

Schwarz, H.-G., Briem, S. & Zapp, P. (2001). Future carbon dioxide emissions in the global material flow of primary aluminium. *Energy*, 26, 775-795.

Shah, R.P., Gararia, S.N., & Singh, R.J. (2004). Alumina refinery brownfield expansion – The Hindalco experience. *Light Metals 2004*, 115-119.

Sidrak, Y.L. (2001). Dynamic simulation and control of the Bayer process. A review. *Ind. Eng. Chem. Res.*, 1146-1156.

Smirnov, V. (1996). Alumina production in Russia part I: Historical background. JOM 48 (8), 24-26.

Smith, P. (2009). The processing of high silica bauxites – review of existing and potential processes. *Hydrometallurgy*, 98, pp 162-276.

Statistics Norway (2010). Energy prices in establishments in manufacturing, mining and quarrying, by industry subclass and energy type measured in øre per kWh. Final Figures 2008.

Steinhurst, W., Knight, P. and Schultz, M. (2012). Hydropower Greenhouse Gas Emissions – State of the Research, Synapse Energy Economics, Inc. Cambridge, M.A.

Storesund, S. (2012). Bauxite and alumina – Industry analysis and commercial strategy. Hydro presentation. http://www.hydro.com/upload/Documents/Presentations/Other/2012/BA%20Investor%20presentation%20FINAL.pdf

Suss A.G., Paromova I.V., Gabrielyan T.N., Snurnitsyna S.S., Panov A.V., Lukyanov I.V. (2004). Tube digesters: protection of heating surfaces and scale removal. *Light Metals*, 137-142.

Thekdi, A. (2000). Seven ways to optimize your process heat system. http://www1.eere.energy.gov/manufacturing/tech_assistance/pdfs/em_proheat_seven.pdf

Trudeau, N., Tam, C., Graczyk, D., & Taylor, P. (2011). Energy transition for industry: India and the global context. IEA Information paper. Paris, France.

Turton, H. (2002). The aluminium smelting industry: Structure, market power, subsidies and greenhouse gas emissions. The Australia Institute. Discussion paper No.4.

United Company Rusal Limited (UC RUSAL) (2010). French listing prospectus. http://rusal.ru/upload/uf/9c0/RUSAL_French_Prospectus.pdf. Accessed at 8 March 2013.

United Company Rusal Limited (UC RUSAL) (2013). Aluminium production costs. http://www.rusal.ru/en/aluminium/energetics.aspx. Accessed at 8 March 2013.

United States Department of Energy (U.S. DOE) (2002). United States Industrial Electric Motor Systems Market Opportunities Assessment. Office of Industrial Technologies. Washington, DC.

United States Department of Energy (U.S. DOE) (2004). Improving Process Heating System Performance: A Sourcebook for Industry. Industrial Technologies Program. Washington, DC.

United States Geological Survey (USGS) (1998). Primary aluminium plants worldwide – 1998, Part I – Detail. Reston, United States.

United States Geological Survey (USGS) (2007a). 2005 Minerals yearbook – Bauxite and alumina. Reston, United States.

United States Geological Survey (USGS) (2007b). 2006 Minerals yearbook – Bauxite and alumina. Reston, United States.

United States Geological Survey (USGS) (2010a). 2007 Minerals yearbook – Bauxite and alumina. Reston, United States.

United States Geological Survey (USGS) (2010b). 2008 Minerals yearbook – Bauxite and alumina [advance release]. Reston, United States.

United States Geological Survey (USGS) (2011). 2009 Minerals yearbook – Bauxite and alumina [advance release]. Reston, United States.

United States Geological Survey (USGS) (2012a). 2011 Minerals Yearbook - Aluminum [advance release]. Reston, United States.

United States Geological Survey (USGS) (2012b). 2011 Minerals Yearbook - Bauxite and Alumina [advance release]. Reston, United States.

Wiedmann, T.O, Schandl, H., Lenzen, M., Moran, D., Suh, S., West, J., Kanemoto, K. (2013). The material footprint of nations. Proc. Natl. Acad. Sci. U.S.A. 2013.

Williams F., & Schmidt, H.-W. (2012). Flash- and CFB calciners, history and difficulties of development of two calcination technologies. *Light Metals*, 135-140.

Wind, S., & Raahauge, B.E. (2013). Experience with commissioning new generation gas suspension calciner. *Light Metals*, 155-162.

Worrell, E., Price, L., Neelis, M., Galitsky, C., & Nan, Z. (2008). World best practice energy intensity values for selected industrial sectors. Lawrence Berkeley National Laboratory (LBNL). Berkeley, United States.

Worrell, E., Ramesohl, S., & Boyd, G. (2004). Advances in energy forecasting models based on engineering economics. *Annual Review Environmental Resources*, 29, 345-381.

Yanjia, W., & Chandler, W. (2009). The Chinese nonferrous metals industry – energy use and CO_2 emissions. *Energy Policy*, 38, 6475-6484.

Chapter 4

ADVANCE. ADVANCE WIKI. 2015 [cited 2015 01-05]; Available from: https://wiki.ucl.ac.uk/display/ADVIAM/Models; http://www.fp7-advance.eu/content/model-documentation.

Akimoto, K., F. Sano., J. Oda, T. Homma, U.K. Rout, and T. Tomoda. (2008). Global emission reductions through a sectoral intensity scheme. Climate Policy, 8. p. S46-S59.

Akimoto, K., F. Sano, T. Homma, J. Oda, M. Nagashima, and M. Kii. (2010). Estimates of GHG emission reduction potential by country, sector, and cost. *Energy Policy*, 38, p. 3384-3393.

Allwood, J. M., M.F. Ashby, T.G. Gutowski, and E. Worrell. (2011). Material efficiency: A white paper. *Resources, Conservation and Recycling*, 55(3), 362-381. https://doi.org/http://dx.doi.org/10.1016/j.resconrec.2010.11.002

Anandarajah, G., S. Pye, W. Usher, F. Kesicki, and C. Mcglade. (2011). TIAM-UCL Global model documentation, University College London: London, United Kingdom.

Bouwman, A.F., T. Kram, and K.K. Goldewijk. (2006). Integrating modelling of global environmental change. An overview of IMAGE 2.4, Netherlands Environmental Assessment Agency (MNP): Bilthoven, the Netherlands.

Brenkert A.L., S.J. Smith, S.H. Kim, and H.M. Pitcher. 2003. Model Documentation for the MiniCAM, in PNNL-14337, Pacific Northwest National Laboratory: Richland, Washington.

Calvin, K., L. Clarke, V. Krey, G. Blanford, K. Jiang, M. Kainuma, E. Kriegler, G. Luderer, and P.R. Shukla. (2012). The role of Asia in mitigating climate change: results from the Asia modeling exercise. *Energy Economics*, 34, S251-S260.

Calvin, K., M. Wise, D. Klein, D McCOLLUM, M. Tavoni, B. van der Zwaan, and D.P. van Vuuren. (2013). A multi-model analysis of the regional and sectoral roles of bioenergy in near-and long-term CO 2 emissions reduction. Climate Change Economics, 4(04), 1340014.

Criqui, P. (2009). The Poles model, Laboratoire d'Economie de la Production et de l'Intégration Internationale (LEPII).

U.S. EPA. 2013. Global Change Assessment Model (GCAM) – General information. Available from: http://cfpub.epa.gov/crem/knowledge_base/crem_report.cfm?deid=212503.

Fujimori, S., T. Hasegawa, T. Masui, and K. Takahashi. (2014a). Land use representation in a global CGE model for long-term simulation: CET vs. logit functions. *Food Security* 6(5), p. 685-699.

Fujimori, S., M. Kainuma, T. Masui, T. Hasegawa, and H. Dai. (2014b). The effectiveness of energy service demand reduction: A scenario analysis of global climate change mitigation. *Energy Policy*, 2014b. 75(0): p. 379-391.

Fujimori, S., T. Masui, and Y. Matsuoka. (2014b). Development of a global computable general equilibrium model coupled with detailed energy end-use technology. *Applied Energy* 128(0), p. 296-306.

GCAM. GCAM Wiki. 2015; Available from: http://wiki.umd.edu/gcam/index.php/Main_Page.

Girod, B., D.P. van Vuuren, M. Grahn, A. Kitous, S.H. Kim, and P. Kyle. (2013). Climate impact of transportation A model comparison. *Climatic Change*, 118(3-4), 595-608.

Harder, J. (2008). Outlook on the global cement and clinker trade. ZKG INTERNATIONAL, 61.6(36).

Hasegawa, T., S. Fujimori, Y. Shin, K. Takahashi, T. Masui, and A. Tanaka. (2014). Climate Change Impact and Adaptation Assessment on Food Consumption Utilizing a New Scenario Framework. Environmental Science & Technology, 48(1), p. 438-445.

Hasegawa, T., S. Fujimori, K. Takahashi, and T. Masui. (2015). Scenarios for the risk of hunger in the twenty-first century using Shared Socioeconomic Pathways. Environmental Research Letters, 10(1), 014010.

IEA. (2010). Energy Technology Perspectives: Scenarios & Strategies to 2050.

IEA. (2011). Energy Balances 2011 edition with 2009 data.

IEA. (2012a). Energy Balances of non-OECD countries 2012 edition with 2011 data.

IEA. (2012b). Energy technology perspectives 2012 - pathways to a clean energy system.

IEA. (2013). World Energy Outlook 2013. IEA. https://doi.org/10.1787/weo-2013-en

IEA. (2015). Energy Balances of OECD countries 2015 edition.

IIASA. MESSAGE. 2012 [cited 2014 10/06]; Available from: http://www.iiasa.ac.at/web/home/research/researchPrograms/Energy/MESSAGE.en.html.

IPCC. (2014a). Assessing Transformation Pathways. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change

IPCC. (2014b). Industry. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate

Change (O. [Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Ed.). Cambridge University Press.

JGCRI. Joint Global Change Research Institute (JGCRI). (2014) [cited 2014; Available from: http://www.globalchange.umd.edu/models/.]

JRC/IPTS. (2010). Prospective study on long-term energy systems – POLES manual version 6.1. .

JRC/IPTS. (2020). Prospective study on long-term energy systems – POLES manual version 6.1, 2010, Joint Research Centre.

Kermeli, K., W. Graus, and E. Worrell. (2014). Energy efficiency improvement potentials and a low energy demand scenario for the global industrial sector. Energy Efficiency, 7(6), 987-1011.

Krey, V. (2014). Global energy-climate scenarios and models: a review. Wiley Interdisciplinary Reviews: Energy and Environment, 3(4), 363-383.

Kriegler, E., K. Riahi, N. Bauer, V.J. Schwanitz, N. Petermann, V. Bosetti, A. Marcucci, S. Otto, L. Paroussos, S. Rao-Skirbekk, T.A. Currás, S. Ashina, J. Bollen, J. Eom, M. Hamdi-Cherif, T. Longden, A. Kitous, A. Méjean, F. Sano, M. Schaeffer, K. Wada, P. Capros, D.P. van Vuuren, O. Edenhofer, C. Bertram, R. Bibas, J. Edmonds, N. Johnson, V. Krey, G. Luderer, D. McCollum, and K. Jiang. (2015). A short note on integrated assessment modeling approaches: Rejoinder to the review of “Making or breaking climate targets — The AMPERE study on staged accession scenarios for climate policy”. Technological Forecasting and Social Change, 99, 273-276. https://doi.org/http://dx.doi.org/10.1016/j.techfore.2015.07.011

Kriegler, E., J.P. Weyant, G.J. Blanford, V. Krey, L. Clarke, J. Edmonds, A. Fawcett, G. Luderer, K. Riahi, and R. Richels. (2014). The role of technology for achieving climate policy objectives: overview of the EMF 27 study on global technology and climate policy strategies. *Climatic Change*, 123(3-4), 353-367.

Liu, N., and Ang, B. (2007). Factors shaping aggregate energy intensity trend for industry: Energy intensity versus product mix. Energy Economics, 29(4), 609-635.

Löschel, A. (2002). Technological change in economic models of environmental policy: a survey. *Ecological economics*, 43(2), 105-126.

Oda, J., K. Akimoto, F. Sano, T. Homma, and T. Tomoda. (2007). Evaluation of energy saving and CO2 emission reduction technologies in energy supply and end-use sectors using a global energy model. *IEEJ Transactions on Electrical and Electronic Engineering*, 2(1), p. 72-83.

Oda, J., K. Akimoto, T. Tomoda, M. Nagashima, K. Wada, and F. Sano. (2012). International comparison of energy efficiency in power, steel and cement industries. *Energy Policy*, 44, p. 118-129.

Oda, J., K. Akimoto, T. Tomoda. (2013). Long-term global availability of steel scrap. *Resources Conservation & Recycling*, 81, p. 81-91.

OECD. (2011). OECD Science, Technology and Industry Scoreboard 2011: Innovation and Growth in Knowledge Economies.

Olivier, J., G. Janssens-Maenhout, M. Muntaen, and J. Peters. (2013). Trend in global CO2 emissions.

Rosen, R. A., & Guenther, E. (2015). The economics of mitigating climate change: What can we know? Technological Forecasting and Social Change, 91, 93-106.

Russ, P., T. Wiesenthal, D. van Regemorter, and J.C. Císcar. (2007). Global Climate Policy Scenarios for 2030 and beyond. Analysis of Greenhouse Gas Emission Reduction Pathway Scenarios with the POLES and GEM-E3 models. JRC Reference Report EUR, 23032.

[Record #190 is using a reference type undefined in this output style.]

Stehfest, E., van Vuuren D.P., L. Bouwman, T. Kram, R. Alkemade, M. Bakkenes, H. Biemand, A. Bouwman, M. den Elzen, J. Janse, P. Lucas, J. van Minnen, C. Müller, and A. Prins. (2014). IMAGE 3.02014, Bilthoven, The Netherlands: PBL Netherlands Environmental Assessment Agency Institute.

Sugiyama, M., O. Akashi, K. Wada, A. Kanudia, J. Li, and J. Weyant. (2014). Energy efficiency potentials for global climate change mitigation. *Climatic Change*, 123(3-4), 397-411.

Thepkhun, P., B. Limmeechokchai, S. Fujimori, T. Masui, R.M. Shrestha. (2013). Thailand's Low-Carbon Scenario 2050: The AIM/CGE analyses of CO2 mitigation measures. *Energy Policy* 62(0), p. 561-572.

UNIDO. (2011). Industrial energy efficiency for sustainable wealth creation. Capturing economic and socal dividends.

USGS. (2013). 2011 Minerals Yearbook – Cement [Advance Release]. http://minerals.usgs.gov/minerals/pubs/commodity/cement/

van der Zwaan, B. C., H. Rösler, T. Kober, T. Aboumahboub, K.V. Calvin, D. Gernaat, G. Marangoni, and D. McCollum. (2013). A cross-model comparison of global long-term technology diffusion under a 2 C climate change control target. *Climate Change Economics*, 4(04), 1340013.

Waisman, H., C. Guivarch, F. Grazi, and J.C. Hourcade. (2012). The IMACLIM-R model: infrastructures, technical inertia and the costs of low carbon futures under imperfect foresight. *Climatic Change*, 114(1), p. 101-120.

WBCSD/CSI-ECRA. (2009). Development of state of the art-techniques in cement manufacturing: Trying to look ahead. http://www.wbcsdcement.org/pdf/technology/Technology%20papers.pdf

WBCSD/CSI. (2012). Global cement database on CO2 and energy information. http://wbcsdcement.org/GNR-2010/index.html

Worrell, E., K. Kermeli, and C. Galitsky. (2013). Energy Efficiency Improvement and Cost Saving Opportunities for Cement Making: An ENERGY STAR Guide for Energy and Plant Managers. http://www.energystar.gov/buildings/sites/default/uploads/tools/ENERGY%20STAR%20Guide%20for%20the%20Cement%20Industry%2028_08_2013%20Final.pdf?7e51-ee82

Zhang, S., E. Worrell, and W. Crijns-Graus. (2015). Synergy of air pollutants and greenhouse gas emissions of Chinese industries: A critical assessment of energy models. Energy, 93, 2436-2450

Chapter 5

ADVANCEwiki. ADVANCE Model description. http://themasites.pbl.nl/models/advance/index.php/ADVANCE_wiki

Akashi, O., T. Hanaoka, Y. Matsuoka, and M. Kainuma. 2011. A projection for global CO2 emissions from the industrial sector through 2030 based on activity level and technology changes. *Energy* 36, 1855-1867.

American Coal Ash Association (ACAA) 2012. 2011 Coal combustion product (CCP) production and use survey.

Anand, S., P. Vrat, and R.P. Dahiya. 2006. Application of a system dynamics approach for assessment and mitigation of CO2 emissions from the cement industry. *Journal of Environmental Management* 79, 383-398.

Association of Canadian Industries Recycling Coal Ash (CIRCA) 2007. Production and use of coal combustion products (CCPs). Production End Use Statistics.

Babiker, M.H., J.M. Reilly, M. Mayer, R.S. Eckaus, I.S. Wing, and R.C. Hyman. 2001. The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Revisions, Sensitivities, and Comparisons of Results. MIT Joint Program on the Science and Policy of Global Change. Boston, United States.

Business New Europe (BNE). 2011. Turkish cement sector. http://www.bne.eu/content/file/dispatch-pdf/2011-05-30/1f65-bneRE.pdf

Central Electricity Authority (CEA) New Delhi 2015. Report on fly ash generation at coal/lignite power stations and its utilization in the country for the year 2014-2015. New Delhi, India.

De Vries, H.J.M., K. Blok, M.K. Patel, M.Weiss, S. Joosen, E. de Visse, and J.Sijm. 2006. Assessment of the interaction between economic and physical growth. EPIST project report UCE-34, prepared by the Netherlands Research programme on Scientific Assessment and Policy Analysis for Climate Change, University of Utrecht, the Netherlands.

Dhadse, S., P. Kumari, amd L.J. Bhagia. 2008. Fly ash characterization, utilization and Government initiatives in India - a review. Journal of Scientific and Industrial Research, vol.67, pp. 11-18.

Edelenbosch, O., K. Kermeli, W. Crijns-Graus, E. Worrell, R. Bibas, B. Fais, S. Fujimori, P. Kyle, F. Sano, and D.P. van Vuuren. 2017. Comparing projections of industrial energy demand and greenhouse gas emissions in long-term energy models. Energy 122, 701-710.

European Cement Research Academy (ECRA), Cement Sustainability Initiative (CSI). 2009. “Development of State of the Art - Techniques in Cement Manufacturing: Trying to Look Ahead”. Düsseldorf, Germany.

European Coal Combustion Products in Europe (ECOBA) 2006. Valuable raw materials for the construction industry. Concrete Plant International (CPI) #4, August 2006.

European Union, 2009. Evaluation of costs of the Russian cement industry’s transition to BAT. Activity Cluster 1 National environmental harmonisation strategy, legal gap analysis. Moscow, Russia.

EFDA (2004). EFDA World TIMES Model, Final report, prepared by ORDECSYS, KanORS, HALOA, KUL. www.efda.org

The European Cement Association (CEMBUREAU). 2013. World statistical review 2001-2011. Brussels, Belgium.

The European Cement Association (CEMBUREAU). 1999. Best Available Techniques for the cement industry. Reference Document. Brussels, Belgium. http://193.219.133.6/aaa/Tipk/tipk/4_kiti%20GPGB/40.pdf

The European Cement Association (CEMBUREAU). 2015. End Uses of Cement. Personal Communication

European Commission JRC-IPTS. 2010. IPPC Reference Document on Best Available Techniques (BREF) in the Cement, Lime and Magnesium Oxide Manufacturing Industries, May 2010. http://eippcb.jrc.ec.europa.eu/reference/

Fidjestøl, P. and Dåstøl, M. 2008. The history of silica fume in concrete - from novelty to key ingredient in high performance concrete.

Fujimori, S., T. Masui, and Y. Matsuoka. 2014. Development of a global computable general equilibrium model coupled with detailed energy end-use technology. *Applied Energy* 128, 296-306.

Global Energy Assessment (GEA) – Toward a Sustainable Future. (2012). Cambridge University press, Cambridge UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Luxemburg, Austria.

Groenenberg, H., K. Blok, and J. van der Sluijs. 2005. Projection of energy-intensive material production for bottom-up scenario building. *Ecological Economics* 53, 75-99.

Harder, J. 2010. Outlook on the global cement and clinker trade. Buxtetehude, Germany.

Heidrich, C., H-J. Feuerborn, and A. Weir. 2013. Coal combustion products: A global perspective. 2013 World of Coal Ash (WOCA) Conference – April 22-25, Lexington (KY), United States.

International Cement Review. 2005. The global cement report 6th edition.

Integrated Assessment Modeling Consortium (IAMC). 2014. Fifth Assessment Report (AR5) Scenario Database, hosted by IIASA at https://secure.iiasa.ac.at/webapps/ene/AR5DB/dsd?Action=htmlpage&page=about#intro

International Energy Agency (IEA). 2005. Energy statistics manual. OECD/IEA, Paris, France.

International Energy Agency (IEA). 2007. Tracking industrial energy efficiency and CO_2 emissions. Paris, France.

International Energy Agency (IEA). 2011. Energy technology perspectives 2012 – Pathways to clean energy system. Paris, France.

International Energy Agency (IEA). 2012. Energy Balances 2011 edition with 2009 data. Paris, France.

International Energy Agency (IEA). 2014b. Capturing the multiple benefits of energy efficiency. Paris, France.

International Energy Agency (IEA). 2014c. World Energy Outlook 2014. Paris, France.

International Energy Agency (IEA). 2015. IEA energy balances 2014. OECD/IEA, Paris, France.

International Energy Agency – Energy Technology Systems Analysis Programme (IEA/ETSAP). 2010. Cement Production. Paris, France.

International Energy Agency (IEA). 2017. Energy technology perspectives 2017 – Catalysing Energy Technology Transformations. Paris, France.

Intergovernmental Panel on Climate Change (IPCC). 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme.

Intergovernmental Panel on Climate Change (IPCC). 2014. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Ishikawa, Y. 2007. Research on the quality distribution of JIS Type_II fly ash in Japan. 2007 World Coal Ash (WOCA), May 7-10, 2007, Northern Kentucky, United States.

JRC/IPTS, 2003. Energy consumption and CO_2 emissions from the world cement industry. Joint Research Centre.

Kermeli, K., Graus, W.H.J., and Worrell, E. (2014). Energy efficiency improvement potentials and a low energy demand scenario for the global industrial sector. *Energy Efficiency*.

Kosmatka, S.H., B. Kerkhoff, Panarese, W.C. (2002). Design and control of concrete mixtures. Edition 14th. Portland Cement Association (PCA).

Koteswara, R. D., P.R.T. Pranav, M. Anusha. (2012). Stabilisation of expansive soil with rice husk ash, lime and gypsum – An experimental study. International Journal of Engineering Science and Technology (IJEST). Vo. 3, p. 8076-8085.

Krey V. (2014) Global energy-climate scenarios and models: a review. *WIREs Energy Environ.* 2014, 3, p. 363-383.

Lan, W. and Yuansheng, C. 2007. The application and development of fly ash in China. 2007 World of Coal Ash (WOCA). May 7-10, 2007, Northern Kentucky, United states.

Lokeshappa, B. and Dikshit, A.K. 2011. Disposal and management of fly ash. 2011 International conference on Life Science and Technology. IPCBEE vol.3, Singapore.

Low Carbon Living CRC. 2012. State of Practice: High Volume Applications of Fly Ash and Barriers to Commercialization. Research Project: RP1004-II. An Australian Government Initiative.

Moon, S.T.J.D. 2013. Regulatory and legal applications: Fly ash use in cement and cementitious products. 2013 World Coal Ash (WOCA), April 22-25, 2013, Northern Kentucky, United States.

ODYSSEY 2015. Consumption of household per m^2 for space heating (normal climate). http://www.indicators.odyssee-mure.eu/online-indicators.html

Pardo, N., J. A. Moya, and A. Mercier. 2011. Prospective on the energy efficiency and CO2 emissions in the EU cement industry. *Energy* 36(5), 3244-3254.

Portland Cement Association (PCA). 2012. Cement Outlook. Presentation on PCA Spring Meeting. April, 2012.

Portland Cement Association (PCA). 2014. Cement and Concrete Basics. http://www.cement.org/cement-concrete-basics

Portland Cement Association (PCA) (2014). State-of-the-art report on use of limestone in cements at levels up to 15%. Illinois, United States.

Putilov, V.Y. and Putilova, I.V. 2005. Modern approach to the problem of utilization of fly ash and bottom ash from power plants in Russia. 2005 World Coal Ash (WOCA), April 11-15, 2005, Northern Kentucky, United States.

Research Institute of Innovative Technology for the Earth (RITE). 2009. RITE GHG Mitigation Assessment Model.

Rosen, R.A., and Guenther E. 2015. The economics of mitigating climate change: What can we know? *Technological forecasting & social change* 91, 93-106.

Van Ruijven, B. J., D. P. Van Vuuren, W. Boskaljon, M. L. Neelis, D. Saygin; M. K. Patel. 2016. Resources, Conservation and Recycling, volume 112, pp. 15 – 36.

Ruth, M., E. Worrell, and L. Price. 2000. Evaluating Clean Development Mechanism projects in the cement industry using a process-step benchmarking approach. Ernest Orlando Lawrence Berkeley National Laboratory (LBNL), Berkeley, California.

Sathaye, J., T., Xu, and C. Galitsky. 2010. Bottom-up representation of industrial energy efficiency technologies in Integrated Assessment Models for the cement industry. Ernest Orlando Berkeley National Laboratory (LBNL). LBNL-4395E

Scrieciu, S.S., T. Barker. and F. Ackerman. 2013. Pushing the boundaries of climate economics: critical issues to consider in climate policy analysis. *Ecological Economics* 85, 155-165.

Senapati, M.R. 2011. Fly ash from thermal power plants – waste management and overview. Current Science vol.100, No. 12.

Statistics Canada (Statcan) 2016. Fuel consumed for electric power generation, by electric utility plants. www5.statcan.gc.ca/

United States Energy Information Administration (U.S. EIA) 2016. Electric power monthly - Coal consumption for electricity generation. https://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_2_01_a

United States Environmental Protection Agency (U.S. EPA). 2007. Alternative Control Techniques Document Update - NOx Emissions from New Cement Kilns. Control Technologies for the Cement Industry: Final Report, U.S. EPA, Washington, DC.

United States Geological Survey (USGS) (2002) Minerals Yearbook - Slag-Iron and Steel. United States Geological Survey(USGS).

United States Geological Survey (USGS). 2013. 2011 Minerals Yearbook – Cement [Advance Release].

United States Geological Survey (USGS) (2015). 2013 Minerals Yearbook - Pumice and pumicite [Advance release].

United States Geological Survey (USGS) (2013) Minerals Yearbook - Slag-Iron and Steel.

United States Geological Survey (USGS). various years. Minerals Yearbook – Cement [Advance Release. http://minerals.usgs.gov/minerals/pubs/commodity/cement/

Van der Werf, E. (2008) Production functions for climate policy modeling: An empirical analysis, Energy Economics, Vol.30, pp. 2964-2979.

Van Vuuren, D.P., B.J., Strengers, and H.J.M. De Vries. 1999. Long-term perspectives on world metal use—a system dynamics model. Resources Policy 25, 239–255

Wang, X. and Deng, J. 2015. Advances in utilization of flue gas desulphurization gypsum. 5th International Conference on Advanced Design and Manufacturing Engineering (ICADME, 2015).

World Business Council for Sustainable Development (WBCSD). 2009. The cement sustainability initiative – Cement industry energy and CO2 performance. Washington, 2009.

World Business Council for Sustainable Development (WBCSD). 2014. GNR project reporting CO_2. http://www.wbcsdcement.org/GNR-2012/index.html. Last visited 24/11/2014.

Worldsteel Association (2014). Fact sheet – Steel industry by-products. http://www.worldsteel.org/publications/fact-sheets/content/01/text_files/file/document/Fact_By-products_2014.pdf

Worrell E., K. Kermeli, C. Galitsky. 2013. Energy efficiency improvement and cost saving opportunities for cement making. United States Environmental Protection Agency (U.S. EPA).

Xu, J.-H., Fleiter, T., Eichhammer, W., & Fan, Y. (2012). Energy consumption and CO_2 emissions in China's cement industry: A perspective from LMDI decomposition analysis. *Energy Policy*, 50, 821-832.

Yan, D., Z. Peng, Q. Ding, K.H. Karstensen, C.J. Engelsen, L. Li, Y. Peng, and C. Jiang. 2015. Distribution of Hg, As and Se in material and flue gas streams from preheater–precalciner cement kilns and vertical shaft cement kilns in China. *Journal of the Air & Waste Management Association*, 65, 1002-1010.

Zeynel, C. (2014). Review of 10th global slag Conference 2014. ZAG International. http://www.globalslag.com/conferences/

Zhang S., E. Worrell, and W.C. Graus. 2015. Evaluating the co-benefit potentials of energy efficiency and emission mitigation in the China's cement industry. *Applied Energy* 147, 192-213.

Chapter 6

ADVANCEwiki. ADVANCE Model description. http://themasites.pbl.nl/models/advance/index.php/ADVANCE_wiki

Aguilar-Hernandez, G.A., J.F. Dias Rodriguez, and A. Tukker. (2021). Macroeconomic, social and environmental impacts of a circular economy up to 2050: A meta-analysis of prospective studies. *Journal of Cleaner Production* (278).

Akashi, O., T. Hanaoka, Y. Matsuoka, and M. Kainuma. (2011). A projection for global CO2 emissions from the industrial sector through 2030 based on activity level and technology changes. *Energy* (36), 1855–1867.

Anandarajah, G., S. Pye, W. Usher, F. Kesicki, and C. Mcglade. (2011). TIAM-UCL global model documentation. University College London.

Ayres, R.U. (1987). The Industry-Technology Life Cycle: An Integrating Meta-model? International Institute for Applied Systems Analysis, Laxenburg,

Bohne, R.A., Brattebø, H., Bergsdal, H. and Hovde, P.J. (2006). Estimation of the service life of residential buildings, and building components, in Norway, in Proceedings: The City Surface of Tomorrow, 8–9 June 2006, Vienna, Austria.

Capros, P., D. Van regemorter, L. Paroussos, and P. Karkatsoulis. (2013). GEM-E3 model manual. E3M-Lab, Institute of Computers and Communications Systems National Technical University of Athens.

Clio-Infra. (2018). Clio Infra database, International Institute of Social History, https://clio-infra.eu/ (accessed on March 2018)

Corsten, M. (2009). Global CO2 abatement potential in the iron and steel industry up to 2030. M.Sc. thesis. NWS-S-2009-25. Utrecht University, Utrecht, the Netherlands.

Crompton, P. (2000). Future trends in Japanese steel consumption. *Resources Policy* (26), 103-114.

de Vries H.J.M., D. P. van Vuuren, M.G.J. den Elzen, and M.A. Janssen. (2001). The Targets Image Energy Regional (TIMER) Model - Technical documentation. Report 461502024/2001. Department of International Environmental Assessment, National Institute of Public Health and the Environment (RIVM), Bilthoven, the Netherlands.

Dellink, R., J. Chateau, E. Lanzi, and B. Magné. (2017). Long-term economic growth projections in the Shared Socioeconomic Pathways. *Global Environmental Change* (42), p.200-214.

Edelenbosch, O.Y, K. Kermeli, W. Crijns-Graus, E. Worrell, R. Bibas, B. Fais, S. Fujimori, P. Kyle, F. Sano, D.P. van Vuuren. (2017). Comparing projections of industrial energy demand and greenhouse gas emissions in long-term energy models. *Energy* 122, 701-710.

Fleiter, T., A. Herbst, M. Rehfeldt, and M. Arens. (2019). Industrial Innovation: Pathways to deep decarbonization of Industry. Part 2: Scenario analysis and pathways to deep decarbonization. Fraunhofer ISI.

Fujimori, S., T. Masui, and Y. Matsuoka. (2014). Development of a global computable general equilibrium model coupled with detailed energy end-use technology. *Applied Energy* (128), p. 296-306.

GCAM (2017). Documentation for GCAM v4.3. http://jgcri.github.io/gcam-doc/v4.3/toc.html

Gielen, D.J. (1997). Building materials and CO2 – Western European emission reduction strategies. ECN - The Netherlands Energy Research Foundation ECN-C-97-065.

Gielen, D.J., and van Dril A.W.N. (1997). The basic metal industry and its energy use. Prospects for the Dutch energy intensive industry. ECN - The Netherlands Energy Research Foundation ECN-C-97-019.

Global Energy Assessment (GEA) – Toward a Sustainable Future. (2012). Cambridge University press, Cambridge UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Luxemburg, Austria.

Goel, R., Mohan, D., Guttikunda, S. K., and Tiwari, G. (2016). Assessment of motor vehicle use characteristics in three Indian cities. Transportation Research Part D: Transport and Environment (44), p. 254-265.

Haberl, H., D. Wiedenhofer, D. Virág, G. Kalt, B. Plank, P. Brockway, T. Fishman, D. Hausknost, F. Krausmann, B. Leon-Gruchalski, A. Mayer, M. Pichler, A. Schaffartzik, T. Sousa, J. Streeck, and F. Creutzig. (2020). A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part II: synthesizing the insights. Environmental Research Letters, 15, p. 1-42.

Hatayama, H., I. Daigo, Y. Matsuno, and Y. Adachi. (2010). Outlook of the world steel cycle based on the stock and flow dynamics. *Environ. Sci. Technol*. (44), p.6457-6463.

Hidalgo, I., L. Szabo, J.C. Ciscar, and A. Soria. (2005). Technological prospects and CO2 emission trading analyses in the iron and steel industry: A global model. *Energy* (30), p. 583-610.

Hirato, T., I. Daigo, Y. Matsuno, and Y. Adachi. (2009). In-use stock of steel estimated by top-down approach and bottom-up approach. ISIJ Int. 49 (12), p.1967–1971.

Hu, M., S. Pauliuk, T. Wang, G. Huppes, E. van der. Voet, and D.B. Müller. (2010). Iron and steel in Chinese residential buildings: a dynamic analysis. *Resources, Conservation and Recycling*, 54(9), p.591–600.

Igarashi, Y., E. Kakiuchi, I. Daigo, Y. Matsuno and Y. Adachi. (2008). Estimation of steel consumption and obsolete scrap generation in Japan and Asian countries in the future. ISIJ Int. (48) 696–704.

Intergovernmental Panel on Climate Change (IPCC) (2014). Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland.

International Energy Agency (IEA). (2018). Energy balances 2018 edition with 2017 data. Paris, France.

International Institute for Applied Systems Analysis (IIASA). (2014). AR5 Scenario Database Version 1.0.2. https://tntcat.iiasa.ac.at/AR5DB/dsd?Action=htmlpage&page=about#

Keramidas, K., A. Kitous, J. Després, and A. Schmitz. (2017). POLES-JRC model documentation. EUR 28728 EN, Publications Office of the European Union, Luxembourg.

Keys, A., M. van Hout, and B. Daniëls. (2019). Decarbonisation options for the Dutch steel industry. PBL Netherlands, Environmental Assessment Agency and ECN part of TNO. The Hague, Netherlands.

Komatsu, Y., Y. Kato and H. Mituhashi. (1994). A research on the stock and life time of office buildings in the 4 wards of Tokyo. Strategies & Technologies for Maintenance & Modernization of Building, AIJ, 465, p. 123–132.

Lou, Y., and Shi, L. (2008). Analyzing iron and aluminum stocks in Handan city in 2005. *Resour. Sci.* 30(1), p. 147–152.

Loulou, R. and Labriet, M. (2008). ETSAP-TIAM: The TIMES integrated assessment model Part I: Model structure. CMS (5), p. 7-40.

Luderer, G., M. Leimbach, N. Bauer, E. Kriegler, et al. (2015). Description of the REMIND model (Version 1.6). Potsdam, Germany.

Morfeldt, J., N. Wouter, and S. Silveira. (2013). The future of global steel production – an energy and climate modeling exercise using ETSAP-TIAM and SAAM. 32nd International Energy Workshop, 19-21 June 2013, Paris, France.

Müller, D.B. (2006). Stock dynamics for forecasting material flows – Case study for housing in The Netherlands. *Economical Economics*, 59, p. 142-156.

Müller, D.B., J. Cao, E. Kongar, M. Altonji, P-H. Weiner, and T.E. Graedel. (2007). Service lifetimes of mineral end uses. U.S. Geological Survey, Minerals Resources External Research Program Award Number: 06HQGR0174.

Müller, D.B., T. Wang, and B. Duval. (2011). Patterns of iron use in societal evolution. *Environ. Sci. Technol.*, 45(1), p. 182-188.

Müller, D.B., T. Wang, B. Duval, and T.E. Graedel. (2006). Exploring the engine of anthropogenic iron cycles. *PNAS* (103), no.44, p. 16111-16116.

Neelis, M., and Patel, M. (2006). Long-term production, energy consumption and CO2 emission scenarios for the worldwide iron and steel industry. Utrecht University, Utrecht, the Netherlands.

OECD (2012), OECD Environmental Outlook to 2050: The consequences of inaction, OECD Publishing, Paris, https://dx.doi.org/10.1787/9789264122246-en

OECD/IEA (2016). World Energy Model documentation - version 2016. International Energy Agency, Pari, France.

Panasiyk, D., B. Laratte, and S. Remy. (2016). Steel stock analysis in Europe from 1945-2013. Procedia CIRP (48), p. 348-351.

Pardo, N. and Moya J.A. (2013). Prospective scenarios on energy efficiency and CO2 emissions in the European Iron & Steel industry. *Energy* (54), p. 113-128.

Pauliuk, S., A. Arvesen, K. Stadler, and E.G. Hertwich. (2017). Industrial ecology in Integrated Assessment Models. *Nature Climate Change* 7, p. 13–20.

Pauliuk, S., Milford, R. L., Müller, D.B., and Allwood, J.M. (2013b). The steel scrap age. Environmental Science and Technology, American Chemical Society (ACS), p.3448-3454.

Pauliuk, S., T. Wang, D.B. Müller. (2012). Moving toward the circular economy: the role of stocks in the Chinese steel cycle. *Environ. Sci. Technol.* 46, p. 148–154.

Pauliuk, S., Wang, T., and Müller, D.B. (2013a). Steel all over the world: Estimating in-use stocks of iron for 200 countries. *Resources, Conservation and Recycling*, 71, p. 22-30.

Rincon-Aznar, A., Riley, R. and Young, G. (2017). Academic Review of Asset Lives in the UK, National Institute of Economic and Social Research (NIESR) Discussion Papers 474, National Institute of Economic and Social Research.

Seo, S. and Hwang, Y. (2011). An estimation of construction and demolition debris in Seoul, Korea: Waste amount, type, and estimating model. *Journal of the air & waste management* 49:8, p. 980-985.

Shyam, S., Verma, H. N. and Bhargava, S. K. (2006). Air pollution and it's impacts on plant growth. New India Publishing Agency, Pitam Pura, New Delhi, India.

The WITCH team (2017). WITCH model documentation. http://www.witchmodel.org/

Toi, A. and Sato, J. (1998). Evaluation of material recycling system with logit model. Tetsu-to-Hagane, 84(7) p. 534-539. https://doi.org/10.2355/tetsutohagane1955.84.7_534

United Nations Environmental Protection (UNEP). (2002). Global Environment Outlook 3; Past, present and future perspectives. London, UK, Earthscan. http://www.unep.org/GEO/geo3/index.htm

van Ruijven, B. J., D. P. Van Vuuren, W. Boskaljon, M. L. Neelis, and D. Saygin; M. K. Patel. (2016). *Resources, Conservation and Recycling* (112), p. 15 – 36.

Van Vuuren D.P., B.J. Strengers, and H.J.M de Vries. (1999). Long-term perspectives on world metal use - a system-dynamics model. *Resource Policy* (25), 239-255.

van Vuuren, D. P., E. Stehfest, D.E.H.J. Gernaat, J.C. Doelman, M. van den Beg, M. Harmsen, H. S. de Boer, L.F. Bouwman, V. Daioglou, O.Y. Edelenbosch, B. Girod, T. Kram, L. Lassaletta, P.L. Luca ", H. van Meijl, C. Müller, B.J. van Ruiven, S. van der Sluis, and A. Tabeau. (2017). Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. *Global Environmental Chang*e (42) p. 237-250.

Wang, K., C. Wang, X. Lu, and J. Chen. (2007). Scenario analysis on CO2 emissions reduction potential in Chinas iron and steel industry. *Energy Policy* (35), p. 2320-2335.

Wang, P., W. Li, and S. Kara. (2017). Cradle-to-cradle modeling of the future steel flow in China. *Resources, Conservation and Recycling* (117), p. 45-57.

Wang, P., Z. Jiang, X. Geng, S. Hao, and X. Zhang. (2014). Quantification of Chinese steel cycle flow: Historical status and future options. *Resources, Conservation and Recycling* (87), p. 191-199.

Watari, T., K. Nansai, D. Giurco, K. Nakajima, B. McLellan, and C. Helbig. (2020). Global metal use targets in line with climate goals. Environ. Sci. Technol. ASAP

World Steel Association (2019). World steel in figures 2019. https://www.worldsteel.org/

World Steel Association (2018). Steel statistical yearbook 2018. Worldsteel Committee on Economic Studies. Brussels, Belgium.

Worrell, E., L. Price, N. Maarten. (2007). World best practice energy intensity values for selected industrial sectors. Lawrence Berkeley National Laboratory (LBNL).

Yin, X. and Chen, W. (2013). Trends and development of steel demand in China: A bottom-up analysis. *Resources Policy* (38), p. 407-415.

Yue, Q., H. Wang, C. Gao, T. Du, M. Li, and Z. Lu. (2016). Analysis of iron in-use stocks in China. *Resources Policy* (49), p. 315-322.

Zhou, S., G.P. Kyle, S. Yu, L.E. Clarke, J. Eom, P. Luckow, V. Chaturvedi, X. Zhang, and J.A. Edmonds. (2013). Energy use and CO2 emissions of China’s industrial sector from a global perspective. *Energy Policy* (58), p. 284–294.

Zhou, W., A. Moncaster, D. M. Reiner, and P. Guthrie. (2019). Estimating Lifetimes and Stock Turnover Dynamics of Urban Residential Buildings in China. *Sustainability*, 11, p. 1-18.

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Curriculum Vitae

Katerina Kermeli was born on the 3rd of December 1982 in Larissa, Greece where she grew up. In 2000 she finished her high school and went to the Aristotle University of Thessaloniki to study Physics with a specialization in Electronics. In 2008 she pursued an M.Sc. degree on Sustainable Development at Utrecht University. Her master internship was conducted at TNO, department of Klimaat, Lucht en Duurzamheid. Since 2011 she worked as a researcher at Utrecht University, in the field of industrial energy efficiency and decarbonization for clients such as the U.S. Department of Energy, the European Commission, the Institute of Industrial Productivity and Greenpeace. Part of the work carried out at Utrecht University has been combined into this Ph.D. thesis.