Modeling the cement industry in integrated assessment models: key factors for further improvement

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Abstract

Energy models, such as Integrated Assessment Models (IAMs), are widely used in the forecasting of energy consumption and greenhouse gas (GHG) emissions and in the analysis and evaluation of the different GHG mitigation options. To construct efficient industry specific policies it is important to make careful estimations of the potentials for energy and GHG savings and the associated costs of mitigation that take into account the individual characteristics of the sector. However, many energy models are lacking on technological detail with many of them assessing the industry as a whole with only limited sub-sector division. In this analysis, the main parameters in modeling the cement industry, such as cement demand drivers, production technology representation and retrofitting options, were identified and a number of simple methodological modeling improvements were composed to assist the less detailed models incorporate more bottom-up sectoral information. Some of the improvements were implemented by two IAMs, POLES and IMAGE. Initial results obtained after the implementation of a number of suggested improvements showed the importance of using recent data that take into account recent industrial developments to construct the baseline and data that take into account regional differences.

Introduction

The industrial sector consumes significant amounts of energy. In 2011, the industrial sector consumed 107 EJ and emitted 10.6 $GtCO_2$, being responsible for 29 % of global energy consumption and about 35 % of energy related emissions (IEA, 2014a). The International Energy Agency (IEA) (2014c) forecasts that without any further actions taken, by 2040, industrial energy use will reach 171 EJ and CO_2 emissions will amount to 15 $MtCO_2$; that is 30 % and 33 % of global energy use and CO_2 emissions, respectively. To identify key strategies for climate change mitigation and construct successful industry specific energy and carbon policies that promote the take-up of energy efficiency and other CO_2 abatement measures it is crucial to effectively analyze the future development of the industrial sector.

Energy models, such as Integrated Assessment Models (IAMs), are increasingly used to project energy demand and greenhouse gases (GHG) and to analyze the potentials and the associated costs of several energy and GHG mitigation options. IAMs are used in major international assessments such as the Intergovernmental Panel of Climate Change (IPCC) special reports, and the Global Energy Assessment (GEA). Accurate estimations on the actual potentials per technology/measure and the associated costs are very important for choosing mitigation options and developing specific policies for climate mitigation. However, in many cases, the level of detail in the industry modules of IAMs is not high enough to make accurate technology comparisons and determine the costs of abating climate change (Sathaye et al., 2010; Rosen and Guenther, 2015) with many of the IAMs assessing the industry in an aggregated manner without sub-sector division.

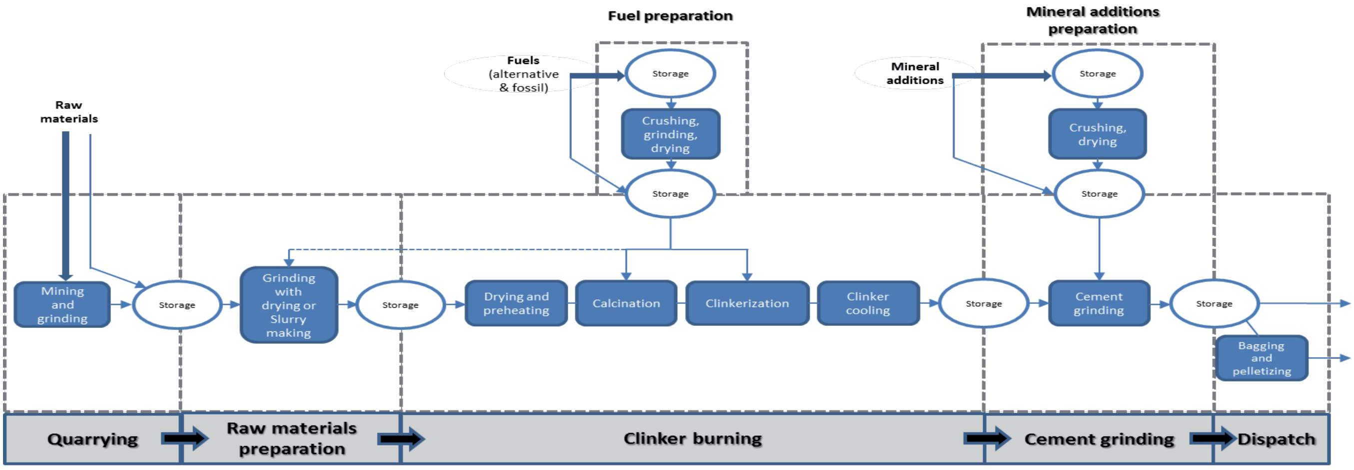

Figure 1. The cement production process (based on CEMBUREAU, 1999).

In this article we investigate how one of the most energy intensive industrial sub-sectors, the cement industry, is modeled in a number of IAMs, and we identify key areas for modeling improvements. This analysis identifies the main parameters and factors that are important in modeling this industry, such as the drivers used to project future cement demand, and the key parameters used in the estimate of energy demand such as production technology representation and energy intensity, retrofitting options and measures for energy savings and CO_2 mitigation, and suggest modeling improvements for energy models. A number of the improvements are implemented by two IAMs, POLES and IMAGE that separately model the cement sub-sector. The old and the updated modeling results are then compared to assess the impact of the modeling changes on the results.

Overview – Cement Industry

Due to its binding properties, cement is mixed with aggregates and water to form concrete[1]. Concrete is a key building material used in the construction of buildings and in infrastructure. For some countries, such as the U.S., infrastructure consumes most cement (50–70 % depending on the year), while in other countries, such as Mexico, Israel and France most cement goes to the construction of residential buildings (CEMBUREAU, 2013; USGS, various years; PCA, 2012; BNE, 2011; International Cement Review, 2005).

There are four main processes involved in cement production (see Figure 1): i) quarrying, ii) raw materials preparation, iii) clinker burning (limestone calcination), and iv) cement grinding. Clinker is the main component of cement and is produced with the calcination of limestone in cement kilns. Clinker production comprises the most energy intensive step, accounting for about 90 % of the overall energy use (Worrell et al., 2013). The clinker production process is also the most CO_2 intensive step as except from the CO_2 emitted from fuel combustion, CO_2 emissions inherent to the clinker production process are released during the calcination of limestone, commonly referred to as process CO_2 emissions (IPCC, 2006)[2]. The type of cement most widely used in concrete production is Portland cement (95 % clinker content) (IPTS/EC, 2010).

Global cement production accounts for 11 % and 26 % of the 2012 industrial energy consumption and emitted CO_2 equivalent, respectively (IEA, 2011). Production has significantly increased since 1960 in all world regions and particularly in Asian countries. In 2012, global cement production reached 3,850 million tonnes (USGS, 2013), triple than 40 years ago. China alone accounts for about 58 % of global production. As the output of the cement industry is directly linked to the state of the construction activity it has been considered that it closely tracks the overall economic situation (CEMBUREAU, 1999).

Cement modeling practices in energy models

MODELING CEMENT DEMAND

Most models that simulate the physical demand of cement are based on the historically observed correlation between the economic activity and material intensity (e.g. Akashi et al., 2011; Anand et al., 2006; Groenenberg et al., 2005; Pardo et al., 2011). The economic activity which is represented by GDP/capita and the material intensity, defined as material used per unit of GDP, is analyzed to derive the correlation parameters of an inverted U-shaped curve. This concept is the Intensity of Use hypothesis, meaning that the shape of the curve depicts the material needs of an economy under different economic phases; at low incomes material intensity is low and increases as the economy moves from agriculture to manufacturing and construction, at high incomes material intensity starts a decreasing trend as the economy starts relying more on services. In addition, at high incomes, two more effects contribute towards a lower material intensity, that is the material substitution with alternative materials and the more efficient use of the material due to technological developments (van Vuuren, 1999; de Vries et al., 2006).

1. Concrete is typically composed of 10–15 % cement, 60–75 % aggregates, 15–20 % water, and 5–8 % air (volume-based) (PCA, 2014).

2. The typical calcination reaction is: $CaCO_3$ + heat → $CaO + CO_2$.

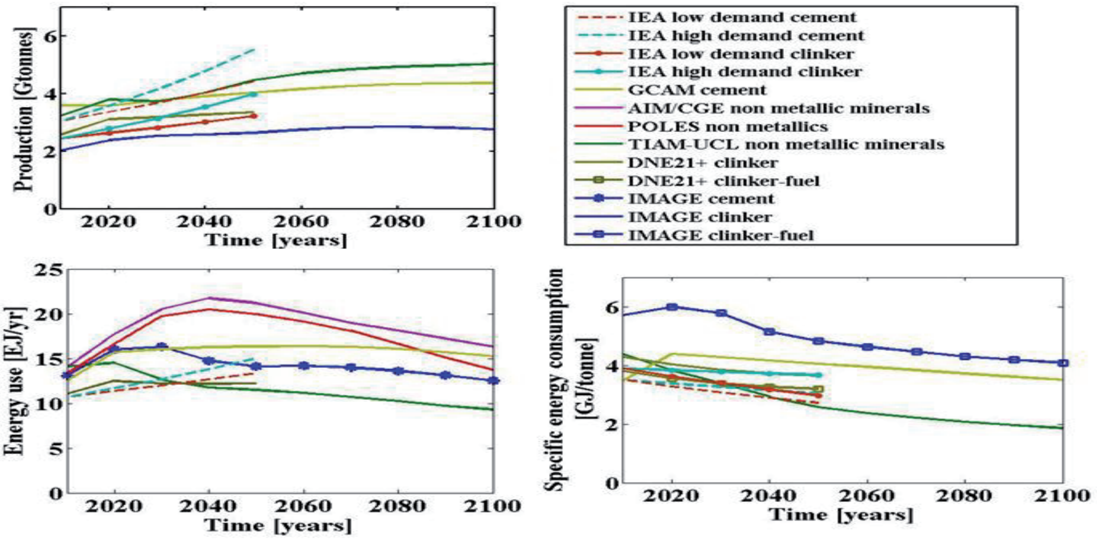

Figure 2. a) Projected material production in the non-metallics/cement industry b) energy use c) specific energy consumption for cement and clinker making in different long-term energy models under the baseline scenario in different long-term energy models in comparison with the IEA projections (Edelenbosch et al., 2015).

MODELING THE ENERGY USE IN THE CEMENT INDUSTRY

At a following step, and after the cement demand is determined in models, an energy intensity value (defined as GJ/tonne cement) is usually used to estimate the energy demand of the sector. In some models, the energy intensity is 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 energy intensity value is used. Similarly, other models might have a regional differentiation of energy intensities while others make the analysis on a global level.

Some of the models do not explicitly model the physical demand of the cement industry but start with directly estimating the energy demand of the sector with the use of production functions. Production functions relate the economic activity (e.g. GDP, value added) and energy prices based on statistical relationships known as "elasticities". The elasticities are estimated based on statistical regression analysis of historical values (Kitous, 2006). In this type of modeling (econometric), energy efficiency is typically represented by the substitution between capital, material, labor and energy inputs.

To understand how the cement industry is currently modeled by the various models we identified the key parameters that play a significant role in the analysis of the cement industry such as demand drivers, technological representation and energy and material efficiency and developed a descriptive questionnaire. The questionnaire has been filled in by six modeling teams, AIM-CGE, DNE 21+, GCAM, IMAGE, POLES and TIAM-UCL, that participated in this study[3]. Key results are outlined in Table 1.

Some models (i.e. POLES), relate the industrial energy demand directly to economic drivers based on historical relationships, while other models (i.e. DNE 21+, IMAGE, TIAM-UCL) relate the material demand to economic drivers. The modeling of cement 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 and more realistic model results.

Most models model the non-metallics minerals sector as a whole. Out of the six energy models only two, DNE 21+ and IMAGE, model the cement industry in a more explicit way. 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 as copper, glass, lime, bricks and tiles which are produced with different processes; industrial subsectors that in general have different characteristics. 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 (see Table 2).

Figure 2 shows the projected material production and energy use for the cement industry of the six energy models under a baseline scenario. For comparison purposes, also the IEA projection for the 6 ˚C scenario (6DS) is shown (IEA, 2012). Figure 2a shows the projected production of cement in the three models (TIAM-UCL, DNE21+, and IMAGE), that explicitly model material demand[4]. All three energy models show demand saturation, 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 2b) while IEA projections show continuous growth rates. Specific energy consumption for cement and clinker making is projected to decline in all models driven by technology development (with exception of the IMAGE results for the first 20 years of the projection).

3. All models presented here are part of the European Union Seventh Framework Programme FP7/2007–2013 ADVANCE project.

4. The DNE21+ and IMAGE models refer to clinker production, while the TIAM-UCL model to non-metallics production.

Table 1. Models participating in this study: main characteristics.

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)
TIAM-UCL	IAM based on bottom-up energy model	Yes	No (non-metallic minerals)

Table 2. Demand drivers in energy models and key cement modeling parameters.

Model	Demand	Technology/Energy use			
	Demand drivers	Production technology	Retrofitting options	Material efficiency	Technological change of production technologies
AIM-CGE	CES[a] production functions[1]	Yes[1]	Yes[2]	No[3]	Yes (exogenously AEEEI)[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[8]	Yes[7]	Yes[7]	No[8]	Yes (exogenously)[3]
GCAM	GDP	With or without CCS[3]	No[3]	No[3] (?)	Yes (exogenously)[3]
IMAGE	Material demand is related to economic activity and material intensity	Yes	No[5]	Yes	Yes (exogenously; AEEI)[3]
POLES	Energy demand depends on energy costs and the Value Added of the sector[3,6]	No	No[9]	No	Yes but not explicitly (energy use per VA can decrease based on price elasticities)[3]
TIAM-UCL	GDP and other economic activity for energy or material demand [3]	Yes[3]	Only CCS[4]	No[3]	Yes (exogenously, AEEI=1%)[4]

[a] *CES (constant elasticity of substitution).*

[1] *Fujimori et al., 2014;* [2] *Babiker et al., 2001;* [3] *Stock-taking exercise results;* [4] *EFDA, 2004;* [5] *Gernaat David, personal communication;* [6] *JRC/IPTS, 2010;* [7] *ADVANCEwiki (https://wiki.ucl.ac.uk/display/ADVIAM/Models);* [8] *RITE, 2009;* [9] *Mima Silvana, personal communication.*

There are several opportunities for improving the modeling of the cement industry in energy models. From modeling the cement demand instead of directly modeling the energy demand, and disaggregating the non-metallics sector to increasing the inclusion of bottom-up information on production technologies on a regional level and taking into account material efficiency.

The following section describes a method that could be used by the less detailed energy models for modeling the cement industry on a regional level. A simple method is presented for estimating:

- the regional base year fuel and electricity use,
- the regional base year energy related and process related CO_2 emissions, and
- a method to account for the deployment of energy and material efficiency.

Guidelines for modeling the cement industry in global energy models

CEMENT DEMAND

To forecast the cement demand, energy models relate GDP growths with historical cement consumption growths. In an attempt to increase the understanding of the underlying processes that drive cement demand this research investigates the relationship between the historical cement demand in the main end-use sector, the residential construction sector, and the floor space area.

Based on information on cement use in the EU countries and on available cement consumption breakdowns of a number of non-European countries, the residential cement use was plotted against the average residential floor space area (see Figure 3). In the case of the EU, cement consumption breakdowns per different construction sector do not take into account the cement use for repair and maintenance purposes. For some countries, the cement use for repairing and maintaining roads, buildings etc. is substantial; Germany (13–40 %), Lithuania (41–54 %), and Estonia 53 % (CEMBUREAU, 2015). However, there is no information on which of the construction activities these cement volumes are consumed.

As seen in Figure 3, the average U.S. residential floor space per capita is almost double the floor space in European countries. The residential floor space area in the U.S. is one of the largest (76 m²/capita), and then follow Norway (59 m²/capita) and the Netherlands (50 m²/capita). This is mainly because in the U.S. wood is another material commonly used in house construction. An increasing trend in the per capita cement use can be observed in the early 2000s for many countries. This is followed by a significant drop in cement use in the late 2000s most probably as an outcome of the slowdown in construction activity during the financial crisis.

Figure 4a shows the per capita cement consumption in the U.S. non-residential sector plotted against the per capita service sector's value added (SVA). It appears that cement use for the construction of non-residential buildings decreases with higher SVA which can be the result of improved material efficiency in combination with an increase in the different materials used in construction such as steel and glass and/or the result of a decrease in the commissioning of new material intensive projects in combination with the completion of older projects. Passenger kilometer, that is the distance travelled by passengers or public transport vehicles, could represent a metric for transportation activity, it was therefore assessed as a driver for cement consumption in the transportation sector. Figure 4b shows the correlation between the cement consumption per capita for road construction and the passenger kilometer developments in the United States. The per capita cement consumption shows an initial increase and after a

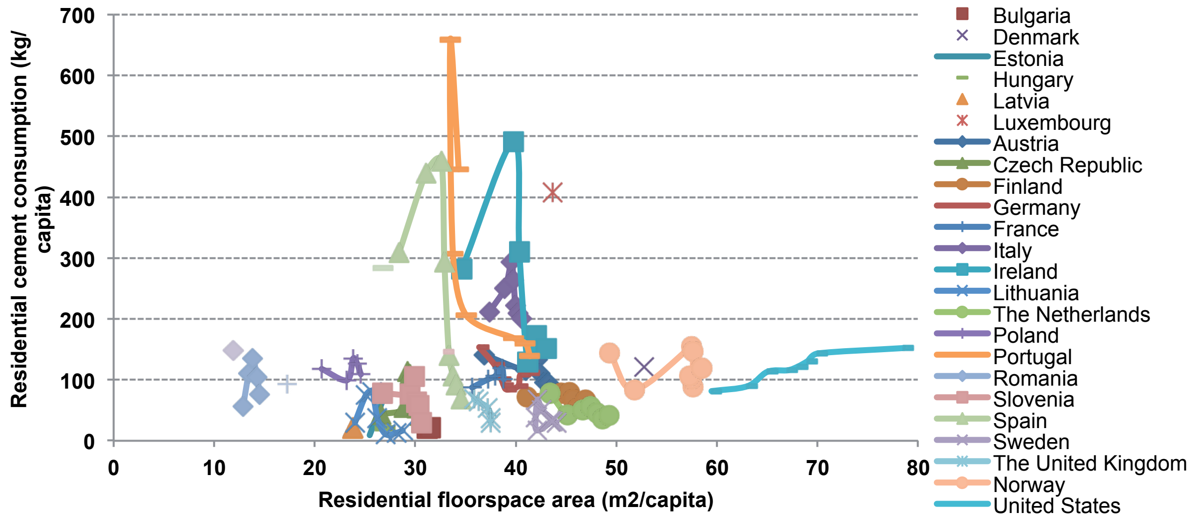

Figure 3. Per capita cement consumption in the residential sector in EU countries (period 2000–2013) and other non-EU (1998–2005) (CEMBUREAU, 2015 and own calculations based on ODYSSEE, 2015; CEMBUREAU, 2013; USGS, various years; PCA, 2012; BNE, 2011; International Cement Review, 2005).

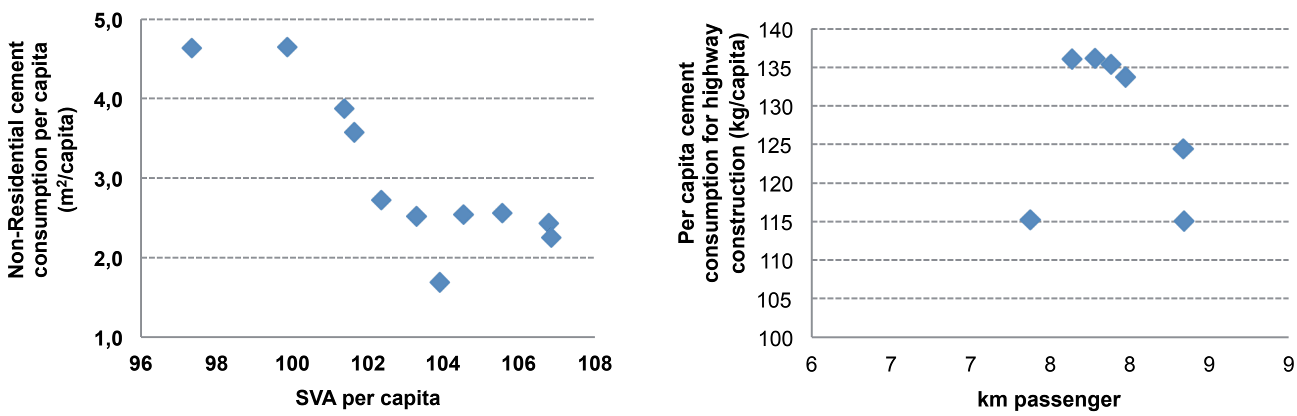

Figure 4. a) U.S. per capita non-residential cement consumption and service sector value added (period 1998–2008) b) U.S. per capita cement consumption for road/highway construction and km passenger (1999–2003 and 2007–2008).

plateau it decreases. The cement consumption for road/highway construction in the U.S. ranges between 120 and 140 kg/capita.

Such an approach for modeling the cement demand is not used by energy models. Although there can be observed a correlation between cement consumption in the different construction sectors (residential, non-residential and infrastructure) and floor space or km passenger, there is a big lack of time series data on the cement use per construction activity for most of the countries that poses a big obstacle in estimating a correlation function that can describe the connection between cement use and construction activity for all regions making the construction of a more bottom-up type of approach of modeling the cement demand not feasible.

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 1). Table 3 shows all variable definitions used in the equations. The most energy intensive step is the calcination of clinker, responsible for the majority of the fuel use (Worrell et al., 2013).

$$E_{total,t} = E_{raw\ material\ pre.,t} + E_{fuel,kiln,t} + E_{el.,kiln,t} + E_{cement\ grinding,t} + E_{additives\ drying,t} \quad (1)$$

Due to the limited regional information, not all variables in Eq. 1 can be defined/determined for every world region. In the following paragraphs we show how the total energy use ($E_{total,t}$), the fuel ($SEC_{thermal,t}$) and electricity ($SEC_{totalel.,t}$) 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 only show a way to determine the total electricity use in cement plants.

Table 3. 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
$SEC_{totalel.,t}$	Electricity use for cement making in year t	GJ/tonne cement
$E_{total,t}$	Total energy use in cement manufacture in year t	PJ
$E_{cementgrinding,t}$	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
$E_{additivesdrying,t}$	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	%

Table 4. Kiln technologies used in the different regions in 2013.

	Dry with preheater and precalciner	Dry with preheater without precalciner	Dry without preheater (long dry)	Semi wet/ semi dry	Wet/shaft kilns
Europe	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	90 %	0 %	0 %	0 %	10 %
CIS	*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 %

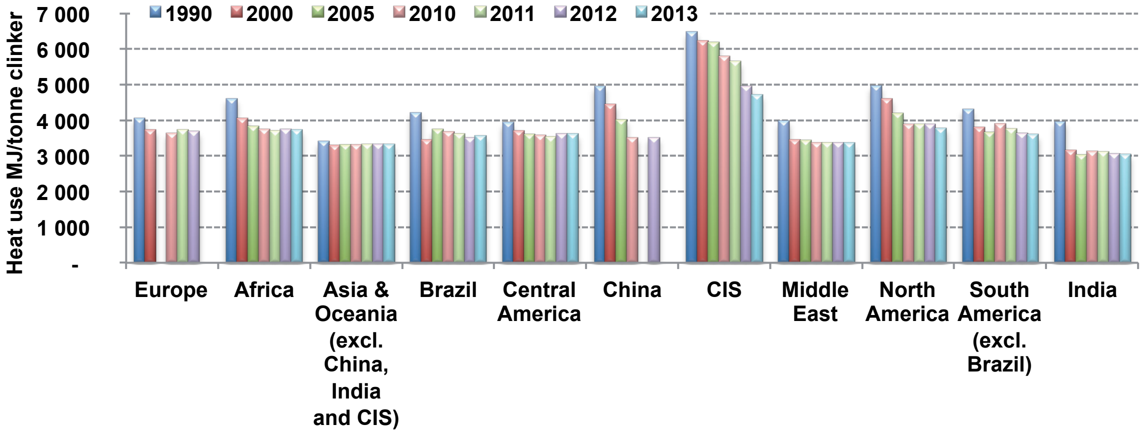

Figure 5. Heat consumption for clinker making per region (WBSCD, 2014; Xu et al., 2012). Heat use for fuel drying is not included.

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 4). Countries with a high share of the wet process will have a higher average fuel use in clinker making. Table 5 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 baseline: 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). 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 4), the typical energy intensities of these technologies (Table 5), and the amount of clinker produced in each region (see Equation 2). 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 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.

$$E_{fuel,kiln,t} = \left(\sum_i Kiln_{ratio,i,t} \times SEC_{thermal,i,t}\right) \times Q_{clinker,t} \qquad (2)$$

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 with the average energy intensity of the technologies shown in Table 5, the estimated fuel use is close (±150 MJ/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 (400–500 MJ/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.

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.

Energy models could develop their baseline 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 shown information to determine the regional electricity use for clinker burning only. In addition, in the same section 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 7).

Approach 2

The electricity use in kilns can be estimated based on the typical energy intensities of the different kiln types and the type of kilns used in each region (see Table 4). About 22 % of the

Table 5. Fuel use by type of kiln technology.

Kiln technology	JRC-IPTS, 2010 (MJ/ tonne clinker)	U.S. EPA, 2007 (MJ/ tonne clinker)	Weighted average (MJ/tonne clinker) (WBCSD, 2009)
Dry with preheater and precalciner	3,000–4,000	2,900–3,800	3,382
Dry with preheater (without precalciner)[1]	3,100–4,200	4,419	3,699
Long dry (without preheater and precalciner)	up to 5,000	5,233	4,489
Semi-wet, semi-dry	3,300–5,400[2]	–	3,844
Wet	5,000–6,400	5,700–10,200 (6,000 typical)	6,343

[1] The energy use differs with the number of preheater stages: 3,400–3,800 MJ/tonne for 3 preheater stages; 3,200–3,600 MJ/tonne for 4 preheater stages; 3,100–3,500 MJ/tonne for 5 preheater stages; 3,000–3,400 for 6 preheater stages (ECRA, 2009).

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

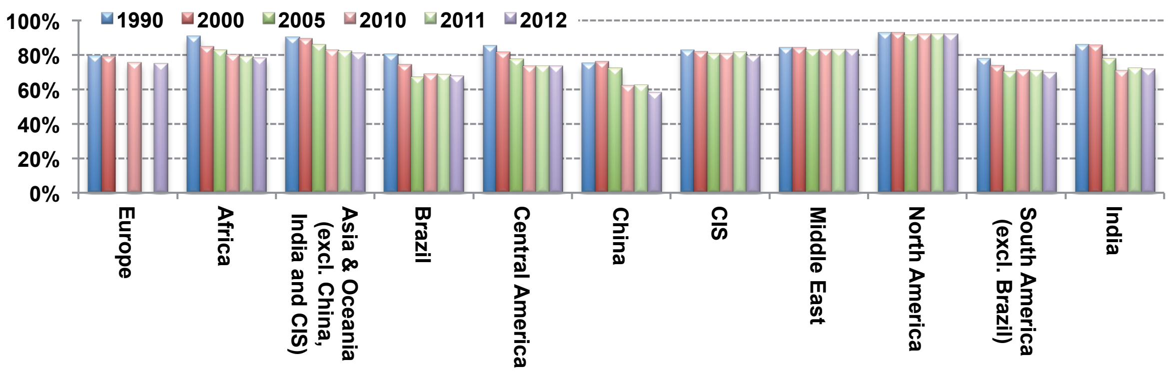

Figure 6. Clinker to cement ratios per region (WBCSD, 2014; Xu et al., 2012; Zhang et al., 2015).

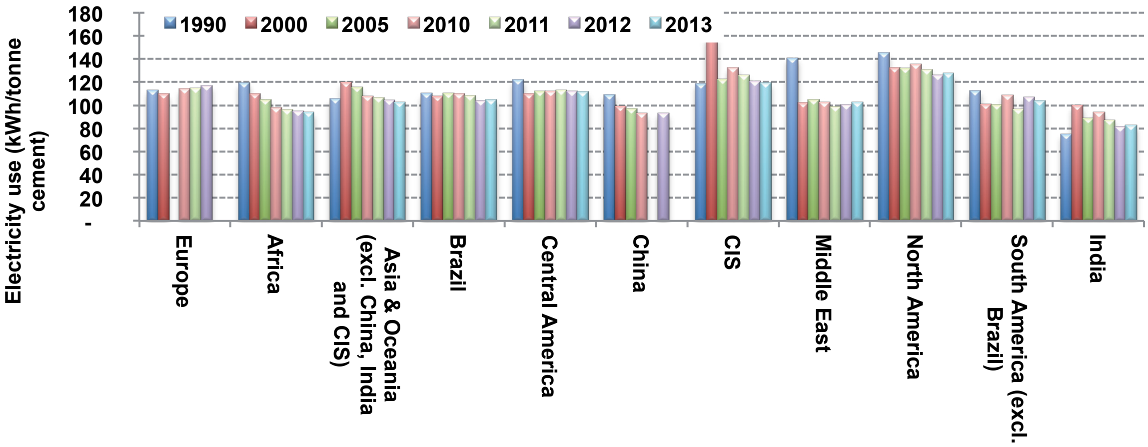

Figure 7. Average electricity consumption for cement making per region (WBCSD, 2014; Xu et al., 2012).

Table 6. 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.

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 therefore estimated from Eq. (3).

$$E_{el.,kiln,t} = \left(\sum_i Kiln_{ratio,i,t} \times SEC_{elec,i,t}\right) \times Q_{clinker,t} \qquad (3)$$

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 of preference (Harder, 2010).

Although there is information available on the typical energy intensities of the various grinding technologies (see Table 6), 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.

Total energy use

The total energy consumption of cement making in the different world regions can thus be estimated by Eq. (4). 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 $E_{cementgrinding,t}$ from Eq. (1) are aggregated into $SEC_{totalel.,t}$.

$$E_{total,t} = \left(\sum_i Kiln_{ratio,i,t} \times SEC_{thermal,i,t}\right) \times Q_{clinker,t} + SEC_{total\ el.,t} \times Q_{cement,t} \qquad (4)$$

A simple way to determine the energy use under a baseline scenario would be to assume that the energy efficiency in cement manufacture improves annually by a certain rate. This improvement on the energy efficiency would 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, the fuel use in clinker production and the 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.

$$CO_{2,total,t} = CO_{2-fuel,t} + CO_{2-process,t} + CO_{2-el.,t} = \sum_j (Fuel_{ratio,j,t} \times CEF_{fuel,j} \times SEC_{thermal,t}) \times Q_{clinker,t} + \sum_i (CEF_{el.,t} \times SEC_{el.,t}) \times Q_{cement,t} + 0.5262 \times Clinker_{ratio,t} \times Q_{cement,t} \quad (5)$$

Figure 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.

ENERGY AND MATERIAL EFFICIENCY

Retrofitting technologies

There is a wide variety of technologies/measures that could be implemented and reduce the energy use and CO_2 emissions in the different process steps in cement manufacture (for more details see Worrell et al., 2013). Most energy models miss the representation of retrofitting technologies in their industry modules. In this paragraph, we show the effect that retrofitting will have as an option for GHG mitigation in the main world regions and suggest ways for incorporating retrofitting in energy models.

i. The technological representation of energy efficiency measures in IAMs could be enhanced with the use of 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-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. 6 and Eq. 7, respectively.

$$CCE = \frac{Annualized\ investment\ cost + Annual\ O\&M\ costs}{Annual\ energy\ savings} \quad (6)$$

The annualized investment cost is a function of the discount rate and the technical lifetime of the technology and can be calculated from Eq. 7.

$$Annualized\ investment\ cost = Investment\ cost \times \frac{d}{(1-(1+d)^{-n})} \quad (7)$$

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

With the use of different energy prices for each country/region some measures that are found to be cost-effective in one country/region might not be cost-effective in another. With the use of cost-supply curves, 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 (measures with high energy savings potential) become cost-effective can be determined.

ii. Another way of incorporating technological detail could be with estimating the Payback period (PBP) for every measure.

All measures can then be ranked based on their PBP. The measures with the lowest PBP will be implemented first (Eq. 8).

$$PBP = \frac{Initial\ investment}{Annual\ opreational\ benefits - Annual\ operational\ costs} \quad (8)$$

iii. 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 how much the energy consumption can decrease and at what cost.

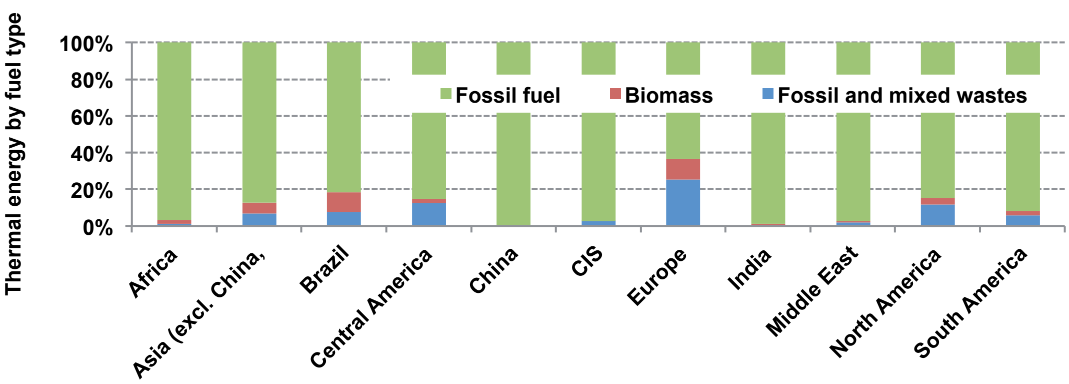

Figure 8. Thermal energy use for clinker making by fuel type (WBCSD, 2014).

In addition, the measures could be clustered in the measures that could decrease the energy use in clinker production (measures that improve the energy efficiency in raw material preparation and clinker burning) and in cement production (measures that improve the energy efficiency in finish grinding). 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. This approach should take into account the technology currently employed in each region.

Material efficiency

Clinker production is the most energy intensive step in cement manufacture. Moreover, clinker making accounts for about two thirds of CO_2 emissions. The adoption of measures that can reduce the clinker content in cement will not only reduce the energy use and the CO_2 emissions from fuel combustion but also reduce the process CO_2 emissions. Reducing the clinker to cement ratio is considered the most effective way of reducing CO_2 emissions and increasing energy efficiency (Huntzinger and Eatmon, 2009).

The type of cement most widely used is Portland cement and has a clinker content of 95 %. Other cement types use a variety of clinker substitutes such as fly ash, pozzolans, granulated blast furnace slag, silica fume, and volcanic ash in various proportions. These substitutes have similar properties to cement and can either be used in the kiln feed (feedstock change) or substitute clinker in the cement or the concrete mix (product change).

To calculate the energy savings from the adoption of lower clinker to cement ratios in each region Eq. (9) could be used:

$$Energy\ savings = SEC_{thermal,t} \times Clinker_{ratio,t} - SEC_{thermal,t} \times Clinker_{New\ Ratio} \quad (9)$$

The development of the clinker to cement ratio in the various world regions can be very hard to forecast, as the use of supplementary cementitious materials depends on several parameters namely (ECRA, 2009): i) availability of supplementary cementitious materials (SCMs), ii) price of clinker substitutes, iii) national standards, iv) market acceptance, and v) cement properties.

Although granulated blast furnace slag (GBFS), fly ash and pozzolanas are materials that are widely available, their regional availability varies significantly. The availability of GBFS depends on the location and output of blast furnaces used for the production of pig iron. It is estimated that about 200 million tonnes of GBFS are produced worldwide (ECRA, 2009). About 275 kg of blast furnace slag are generated for every tonne of crude steel produced with the BF/BOF route (Worldsteel, 2014). Not all BFS is produced as granulated slag, some of the BFS is air-cooled. Air-cooled slag cannot be used for cement production.

The availability of fly ash depends on the total capacity of coal plants. It is estimated that global fly ash production reaches 500 million tonnes (ECRA, 2009). However, not all fly ash is suitable for cement production (VDZ and Penta, 2008). Natural pozzolans are materials of volcanic origin and their availability is strongly dependent on the location. About 5.6 Mtonnes of natural pozzolans are produced worldwide (USGS, 2013).

Another simple way to reduce the clinker content is by adding limestone. Limestone is widely available to cement plants as it is the main raw material used in cement production. The limestone content in cement could be as high as 25–35 % (ECRA, 2009).

A simplified way to model the change in the clinker to cement ratio could be to only consider the availability of raw materials (see Eq. 10). Table 7 shows the variable definitions.

$$Clinker_{ratio,t} = Clinker_{ratio,Portland} - Limestone_{ratio} - \frac{Q_{fly\ ash,t}}{Q_{cement,t}} - \frac{Q_{BFS,t}}{Q_{cement,t}} - \frac{Q_{pozzolanas,t}}{Q_{cement,t}} \quad (10)$$

First test results and discussion

In this section we show the first model results after the implementation of model improvements in modeling the cement industry in IMAGE and POLES. Figure 9 shows the model results on heat use under the baseline scenario before and after the model improvements in the IMAGE model. It shows the heat demand before calibration with more recent data, the calibrated baseline and the calibrated baseline when retrofitting of old plants is also included.

ENERGY USE

Model improvements that took place were:

1. Historical calibration of regional fuel use (MJ/tonne clinker) and electricity use (kWh/tonne cement). Previously, the

Table 7. Variable definition.

Variable	Definition	Unit
$Q_{cement,t}$	Total cement output in year t	Mtonnes cement
$Q_{flyash,t}$	Total fly ash availability in year t	Mtonnes fly ash
$Q_{BFS,t}$	Total granulated blast furnace slag availability in year t	Mtonnes BFS
$Q_{pozzolanas,t}$	Total pozzolanas availability in year t	Mtonnes pozzolanas
$Clinker_{ratio,t}$	The clinker to cement ratio in year t	%
$Clinker_{ratio,Portland}$	The clinker to cement ratio in Portland cement (95 %)	%
$Limestone_{ratio}$	The possible limestone content in cement (10–35 %)	%

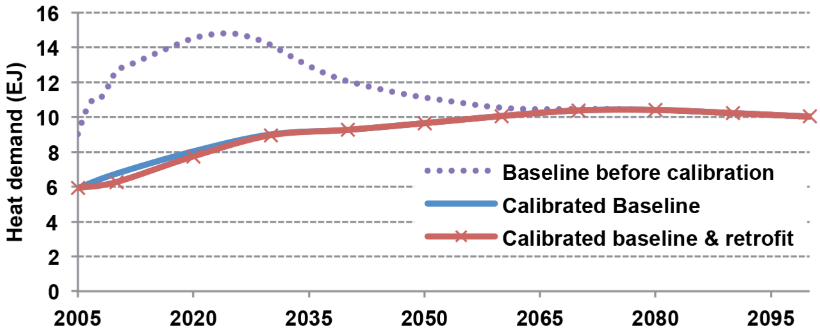

Figure 9. Total heat use for clinker making in IMAGE before and after first improvements.

1970–1990 regional energy intensities were estimated based on energy use data of a limited number of countries. Historical data were updated based on information shown in Figure 5 and Figure 7.

2. Historical calibration of the regional clinker to cement ratio. The regional clinker to cement ratios were also calibrated with the use for more recent data shown in Figure 6.

Previously the heat use per tonne clinker was overestimated for recent years and led to high energy use in the baseline, see "Baseline before calibration" in Figure 9). The use of more recent data had a big impact on the baseline energy use and as a result affects all scenarios and estimations of energy savings and GHG abatement potentials. Chinas' cement industry has in recent years been through great structural changes. New plants were built and old capacities consisting of the more inefficient wet kiln types were decommissioned (Zhang et al., 2015). This resulted in a substantial decrease of the energy use for clinker making. In addition, China has one of the lowest clinker to cement ratios. Revising these key parameters for the base year is therefore crucial, especially for regions/countries with large volumes of cement production such as China (responsible for about 60 % of current cement production).

RETROFITTING/ENERGY EFFICIENCY

Furthermore, an additional model improvement that has been incorporated by the IMAGE model deals with energy efficiency improvement in existing cement plants. Previously in IMAGE, when capacity increased in a specific region 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)"). The model did not deal with improvements in existing cement plants. With the adoption of cost supply curves (see Section in this article on Energy and Material Efficiency), information available on current technology adoption levels and measures for energy efficiency improvement was used to estimate the potentials for regional energy savings in existing plants. When retrofitting opportunities are taken into account the energy demand under the baseline scenario is lower (see Figure 9).

With the use of cost supply curves, measures that are currently considered "cost-effective" (defined as measures were the annualized investment cost per GJ saved is lower than the cost of energy used) or else known as "low-regret" options, measures usually not taken into account in energy models, are also included.

In addition, the function used to assign the choice of future installed cement capacity can be improved by better representing current trends. In new plants built, the modern and efficient technologies are employed with the technology of preference being the efficient dry (Ruth et al., 2000; IEA/ETSAP, 2010).

MATERIAL EFFICIENCY

Improvements on material efficiency modeling have not been yet implemented but are being planned. Currently in IMAGE, the clinker to cement ratio in all regions shows a slight decrease within the 1990–2005 period and from then onwards it decreases in all regions to converge at 74 % by 2050. The development of the clinker to cement ratio could be modeled in a more dynamic way by linking the availability of key supplementary cementitious materials (SCMs) to the output of other modules within the model. Therefore, one of the model improvements will be to link the availability of GBFS to primary steel production and the availability of fly ash to the activity of coal-fired power plants for each region as projected by the model while also taking into account the regional availability of the remaining SCMs. Making this link will have a significant impact on model results as for example in a scenario where many coal-fired power plants are shut down or steel demand weakens, the availability on SCMs will decrease lowering the potential for GHG abatement in the cement industry.

REGIONAL AND SECTORIAL BREAKDOWN

The Poles model, models the non-metallics minerals sector as a whole (see Table 1). However, a detailed cement module in POLES has been constructed (JRC/IPTS, 2003) that was enabled for this testing exercise. In the detailed module, POLES takes into account industry specific characteristics such as variations in regional energy intensities and regional clinker to cement ratios.

As seen in Figure 10, heat use for non-metallics minerals production increases smoothly until 2035 and then faces a decrease. Heat use for cement making (responsible for the majority of the energy use in the non-metallics minerals sector) reaches a peak at about 12 EJ and then drops significantly to less than 8 EJ as a result of a sharp decrease in cement production. IMAGE under the calibrated & retrofit case does only experience a gradual increase. At 2050 both models seem to converge.

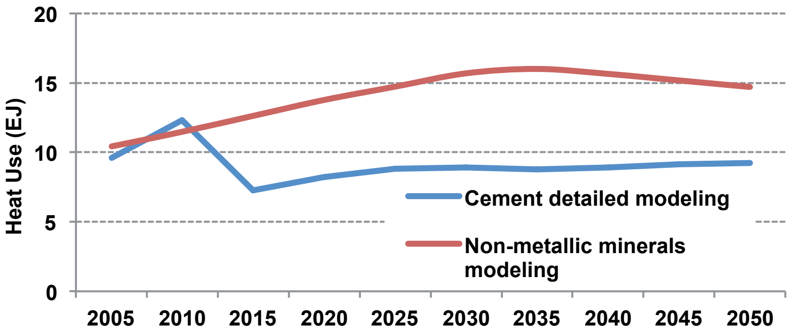

Figure 10. POLES baseline modeling results for heat use for non-metallics minerals and cement making.

Conclusion

The industrial sector is complex, primarily due to its heterogeneity. There is a wide variety of products manufactured e.g. chemicals and petrochemicals, cement, glass, metals such as steel and aluminium that are all produced with different industrial processes. To effectively model the industrial sector it is important to analyze each sub-sector separately in order to include all industry specific characteristics that affect its energy development.

In this analysis we tried to gain some insight into how the cement industry is currently modeled in energy models. For this purpose a questionnaire was filled in by six energy models that either model the cement or the non-metallics industry. It was observed that energy models although they are quite detailed when it comes to the energy supply side, they are too aggregated when it comes to modeling the energy demand side and especially the industrial energy demand. Some of the models do not model the physical demand of cement but instead they directly model the energy demand. This is done by relating the historic energy demand of the sector with the economic activity (e.g. GDP, value added) and energy prices and based on observed statistical relationships project the future cement demand.

In addition, other models do not explicitly model the cement industry but the non-metallics industry. Both of these approaches do not allow for industry specific characteristics and regional differentiations to be taken into account thereby limiting the quality of the modeling results when it comes to the industrial sector.

This article aimed at investigating the modeling of the cement industry in global energy models and to provide basic guidelines and data for adding the modeling of this industrial sub-sector in the models that do not currently model it. Key parameters in modeling the cement industry such as regional energy intensity, CO_2 intensity, technological adoption rate, energy efficiency and material intensity were addressed. All relevant available industry specific information was provided and a simple guideline was formulated for the adoption by energy models so as to better reflect reality.

A number of the proposed guidelines were adopted by the IMAGE model. It was shown that the calibration with more recent data can have a large impact on model outcomes as the cement industry has changed quite drastically in recent years with most of the production taking place in newly built plants in China. Further modeling improvements on including the option of retrofitting can decrease the projected energy use for the coming years especially in regions with old cement plants. The current ongoing implementation of a number of improvements on retrofitting and material efficiency is expected to improve modeling results even further.

More proposals could be suggested that would improve industry representation even more but are not dealt with in this analysis, such as induced technological change (Scrieciu et al., 2013) and the inclusion of multiple benefits of energy efficiency improvement measures (IEA, 2014b).

References

ADVANCEwiki. ADVANCE Model description. https://wiki.ucl.ac.uk/display/ADVIAM/Models

Akashi, O., T. Hanaoka, Y. Matsuoka, and M. Kainuma. 2011. A projection for global CO_2 emissions from the industrial sector through 2030 based on activity level and technology changes. *Energy* 36, 1855–1867.

Anand, S., P. Vrat, and R.P. Dahiya. 2006. Application of a system dynamics approach for assessment and mitigation of CO_2 emissions from the cement industry. *Journal of Environmental Management* 79, 383–398.

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

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.

Edelenbosch, O., K. Kermeli, W. Crijns-Graus, E. Worrell, B. Fais, S. Fujimori, P. Kyle, F. Sano, and D.P. van Vuuren. 2015. Comparing projections of industrial energy demand and greenhouse gas emissions on long-term energy models. Manuscript submitted for publication.

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.

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/

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.

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.

Huntzinger, D.N and Eatmon, T.D. (2009). A life-cycle assessment of Portland cement manufacturing: comparing the traditional process with alternative technologies, *Journal of Cleaner Production* 17, 668–675.

International Cement Review. 2005. The global cement report 6th edition.

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). 2014a. Energy efficiency indicators: Essentials for policy making. 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 – Energy Technology Systems Analysis Programme (IEA/ETSAP). 2010. Cement Production. 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.

JRC/IPTS, Energy consumption and CO_2 emissions from the world cement industry, 2003, Joint Research Centre.

JRC/IPTS, Prospective study on long-term energy systems – POLES manual version 6.1., 2010, 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*.

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 CO_2 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

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.

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.

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). 2013. 2011 Minerals Yearbook – Cement [Advance Release]. http://minerals.usgs.gov/minerals/pubs/commodity/cement/

United States Geological Survey (USGS). various years. Minerals Yearbook – Cement [Advance Release]. http://minerals.usgs.gov/minerals/pubs/commodity/cement/

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.

World Business Council for Sustainable Development (WBCSD). 2009. The cement sustainability initiative – Cement industry energy and CO_2 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.

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.

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