ADVANCE-WP2

Enhancing the representation of energy demand developments in IAM models –

A Modeling Guide for the Cement Industry

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1. Introduction

Cement is an inorganic, non-metallic and finely ground grey powder which when mixed with water forms a paste that sets and hardens. Due to its binding properties, cement is used in combination with aggregates and water to form concrete. The typical cement content in concrete is in the range of 10 and 15% (PCA, 2013).

Concrete is a key building material widely used in the construction of buildings and civil engineering. The type of cement most widely used in concrete production is Portland cement (IPTS/EC, 2010). The output of the cement industry is directly linked to the state of the construction activity and is therefore considered that it closely tracks the overall economic situation (CEMBUREAU, 1999). As shown in Figure 1 cement production has significantly increased since 1960 in all world regions and particularly in Asian countries.

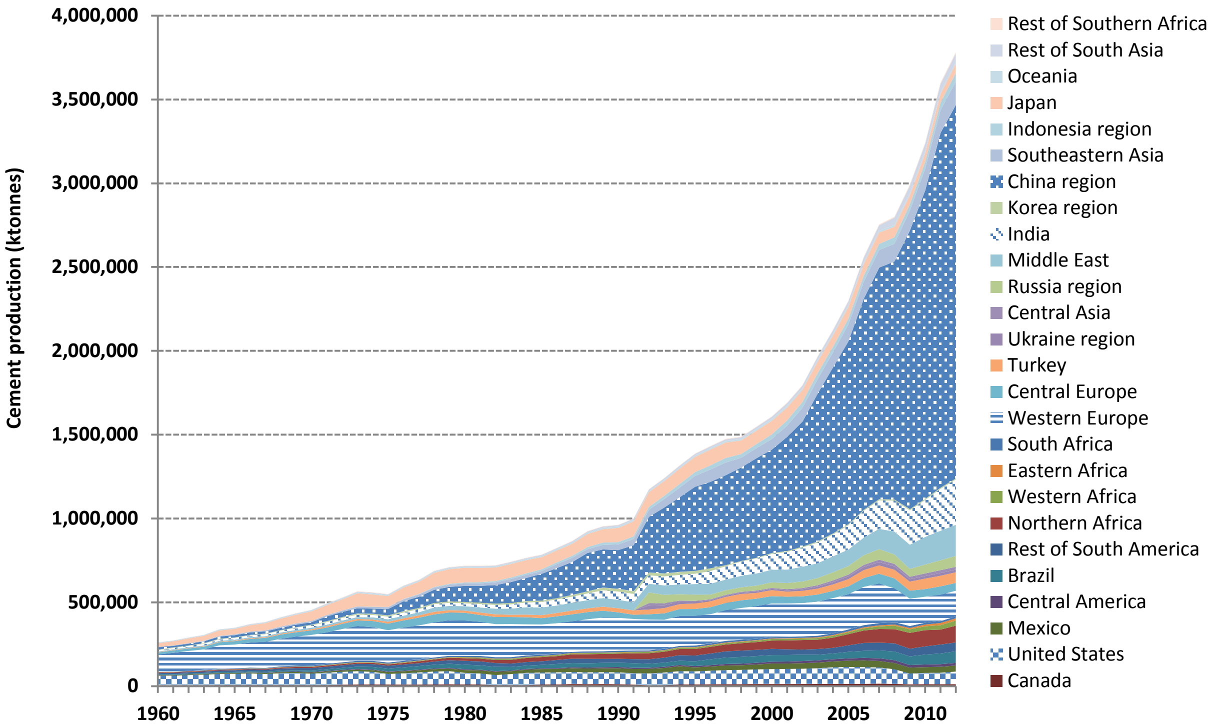

Figure 1 Cement production in the different world regions from 1960 to 2012 (based on USGS, various years)

In 2012 cement production reached 3,850 million tonnes (USGS, 2012). China alone accounted for 58% of global production.

The cement industry is one of the five most energy-intensive industries, accounting for 11% of global industrial energy consumption[1] (see Figure 2). In 2009, the cement industry consumed 11 EJ of which most is fuel (IEA, 2011).

[1] In 2009 the global industrial energy consumption was 105 EJ (including the energy use in coke ovens and blast furnaces and excluding the energy use as feedstock) (IEA, 2011).

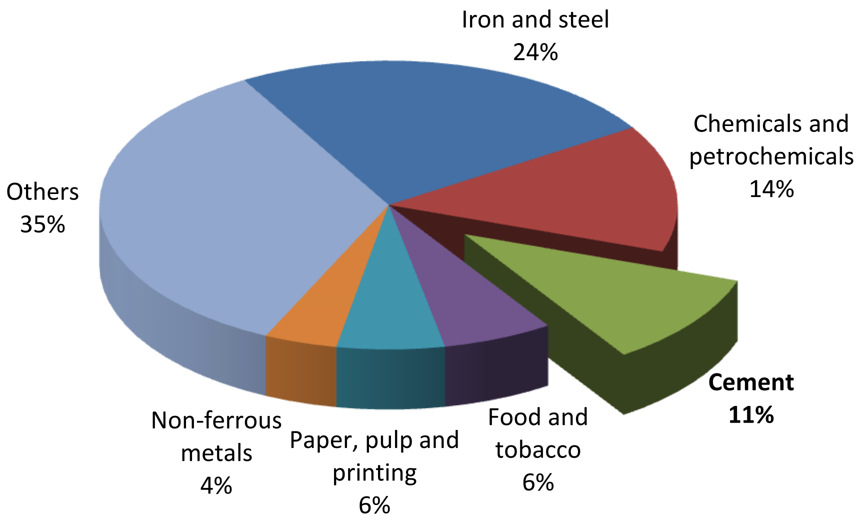

Figure 2 Global industrial energy consumption breakdown per industrial sub-sector in 2009 (based on IEA, 2011). The total final energy use includes the energy use in coke ovens and blast furnaces and excludes the energy use for feedstock purposes

The cement industry is also a significant greenhouse gas emitter. In 2009 2.3 $GtCO_2$ were emitted into the atmosphere (IEA, 2012); about 1.1 $GtCO_2$ were energy related and 1.2 $GtCO_2$ were process related released during the calcination of clinker.

Figure 3 shows the CO_2 emissions breakdown of the various industrial sub-sectors in 2010. The cement industry is the second most CO_2-intensive industry following the iron and steel industry. In 2010 cement production was responsible for about 26% of global industrial CO_2 emissions.

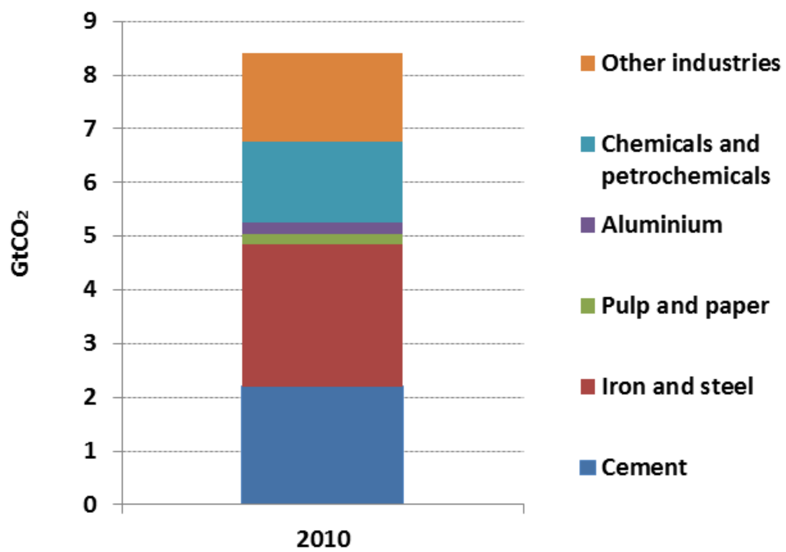

Figure 3 Global industrial CO_2 emission breakdown per industrial sub-sector in 2010 (IEA, 2012)

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. Improving the way the industrial sector is modelled in IAMs is of major importance as it will help to more accurately estimate the regional greenhouse gas (GHG) mitigation potentials per technology/measure and will lead to a better evaluation of the variety of technological options and energy policies that could be implemented.

In this effort, the improvement of the way the cement industry is currently modelled in IAMs has been identified as a key starting point. A number of IAMs model the cement industry explicitly and take into consideration when estimating the sectors energy and emission intensity all important parameters such as the type of production technologies used, clinker production volumes, fuel types and regional variances of the above parameters. However, many IAMs model the non-metallics minerals sector as a whole and only a few models specifically target the cement industry. In addition, a number of models do not explicitly model physical demand but start with relating the energy demand with economic activities missing in this way important industry specific characteristics. These guidelines can be used by the less detailed models to create a module to explicitly model the cement industry.

The cement industry except from being a major industrial energy consumer and GHG emitter is also an industry characterized by limited complexity and can therefore be easier incorporated in existing IAMs than other industrial sub-sectors. Its limited complexity is due to a number of factors. Most of the cement is consumed in a single sector: the construction sector. Therefore, the entire cement consumption could be linked to the 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 used could vary) composed of three main process steps that consume the majority of the energy used: i) raw materials preparation ii) clinker making, and iii) finish grinding.

2. The cement production process

Figure 4 shows the processes involved in cement manufacture; 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 in cement manufacture, accounting for about 90% of the overall energy use. The clinker production process is also the most CO_2 intensive process in cement production as except from the CO_2 emitted from fuel combustion, CO_2 emissions inherent to the clinker production process released during the calcination of limestone are also emitted, commonly referred to as process CO_2 emissions (IPCC, 2006)[2].

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

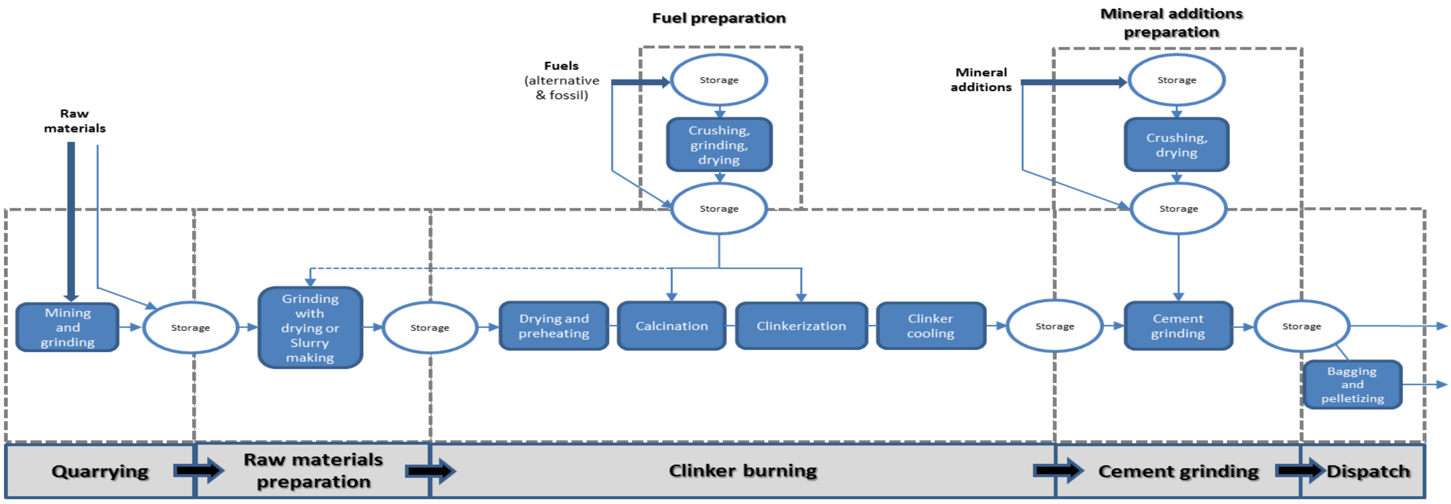

Figure 4 The cement production process (based on CEMBUREAU, 1999)

Raw material quarrying

The main raw materials needed for the manufacture of cement are limestone, chalk, clay and shale. Limestone provides the needed calcium oxide and some of the other oxides, while clay, shale and other materials provide most of the silicon, aluminium and iron oxides. The raw materials are extracted from quarries which are mostly open-pit. The cement plants are most usually situated close to the limestone or chalk quarries. After extraction, the raw materials are crushed, pre-homogenized, ground and proportioned so that the resulting mixture has the desired fineness and chemical composition to be fed in the cement kiln (Worrell et al., 2013).

The power consumption for crushing can range between 0.4 and 1.0 kWh/tonne of raw material (Chatterjee, 2004).

Raw material preparation

After the primary and secondary size reduction, the raw materials are further reduced in size by grinding. There are a variety of grinding technologies used, e.g. ball mills, roller mills and roller presses. The grinding process differs with the type of the kiln used for clinker production. When dry kilns are used, the raw materials are ground into a flowable powder. The typical moisture content of the feed kiln is about 0.5%.

When the raw materials have high moisture content (more than 20%) wet kilns are used in clinker production (IPTS/EC, 2010). In the wet process, the raw materials are ground with the addition of water in ball mills to produce a slurry typically containing 36% water.

Raw material grinding is electricity intensive and can consume 9-32 kWh/tonne raw material (Worrell et al., 2013).

Clinker burning (pyroprocessing)

Clinker production is the most energy-intensive step in cement production, accounting for more than 90% of the total energy use and all of the fuel use. Clinker is produced by pyroprocessing in cement kilns. Cement kilns evaporate the water present in the raw meal, calcine the carbonate, and lastly, form cement minerals (clinker). The produced clinker is then cooled down in coolers.

Clinker is produced with the wet or the dry process. The dry process has lower energy requirements than the wet process due to the lower evaporation needs. To increase the waste heat recovery and thus the overall energy efficiency, dry kilns are equipped with preheater tower systems. The more preheater stages the less energy is consumed. However, when the raw materials or fuel used are very humid, it can be more energy efficient to use fewer preheater stages and use the extra heat for drying (Bolwerk et al., 2006).

More recently, the precalciner technology has been developed in which a second combustion chamber is added between the kiln and the pre-heater system that allows for further reduction of kiln fuel requirements. The most efficient pre-heater, pre-calciner kilns use approximately 2.9 GJ/tonne clinker (IPTS/EC, 2010).

Cement grinding
To produce Portland cement, the cooled cement clinker is ground together with additions (3-5% gypsum to control the setting properties of the cement) in ball mills, ball mills in combination with roller presses, roller mills, or roller presses (Alsop and Post, 1995). To produce blended cements, cement clinker is ground along with other additives, such as granulated blast furnace slag (GBFS), fly ash, natural or artificial pozzolanas and limestone. In some cases these additives need to be dried first.

The electricity use for cement grinding depends on the surface area required for the final product and the additives used. Electricity use for raw meal and finish grinding depends strongly on the hardness of the material (limestone, clinker, pozzolana extenders) and the desired fineness of the cement as well as the amount of additives. Blast furnace slags are harder to grind and hence use more grinding power.

The final product, finished cement is then stored in silos, tested and filled into bags, or shipped in bulk on bulk cement trucks, railcars, barges or ships. Electricity is also consumed for conveyor belts and packing of cement. The total consumption for these purposes is generally low.

3. Modeling energy use and greenhouse gas emissions in cement production

In this section we give a description of the approaches that could be used for modeling the cement industry. In addition, relevant information that could be used in the models such as information on current regional energy intensities, clinker to cement ratios and measures for energy efficiency improvements is also provided, where possible.

Section 3.1 describes two approaches that could be used for modeling the cement demand and cement production. After the cement production is determined, Section 3.2 follows, where a description is given on the way the energy use for cement making could be modelled. Section 3.3 focuses on the measures that could decrease the energy consumption and therefore the CO_2 emissions, and information is provided on the energy savings potentials and the associated investment costs. Section 3.4 presents the way the greenhouse gas emissions (GHGs) from cement production could be modelled and Section 3.5 presents the ways the clinker to cement ratio could be reduced.

3.1. Modeling the cement demand and production

Most models that simulate the physical demand of cement are based on the historically observed correlation between the economic activity and material intensity and the product demand (e.g. Akashi et al., 2011; Anand et al., 2006; Groenenberg et al., 2005; Pardo et al., 2011).

To increase the understanding of the underlying processes that drive cement demand and construct a more bottom-up type of approach for the forecasting of cement demand developments, the relationship between the historical cement demand in the different construction sectors and the floorspace area of these specific sectors was investigated. Paragraph 3.1.1 shows how cement consumption could be modelled with the use of function relations between cement use and some construction activity indicators and paragraph 3.1.2 shows how cement consumption could be modelled based on monetary indicators.

3.1.1 Cement consumption and construction activity

Cement is consumed in a variety of construction projects mainly divided into the construction of i) residential buildings, ii) non-residential buildings, and iii) infrastructure. Residential buildings include buildings built for housing purposes. Non-residential buildings comprise industrial, commercial, educational, health and other type of buildings not used for residential purposes. Infrastructure includes the construction of roads, bridges, sewage systems etc. Table 1 shows the cement consumption broken down per construction activity in the countries for which data is available.

Table 1 Cement consumption per different construction activity (CEMBUREAU, 2013; USGS, various years; PCA, 2012; BNE, 2011; International Cement Review, 2013)

Country/region	Year	Residential buildings (% of total)	Non-residential buildings (% of total)	Infrastructure (% of total)[2]	Resid. Cement Consumption (ktonnes)	Non-Resid. Cement Consumption (ktonnes)	Infr. Cement Consumption (ktonnes)	Road/highway construction (% of Infrastructure)
United States	1998	22%	27%	51%[1]	22,500	27,000	51,667	
United States	1999	24%	26%	50%[1]	25,000	28,000	53,320	60%
United States	2000	30%	22%	48%	32,000	24,000	51,669	74%
United States	2001	30%	20%	50%	33,000	22,500	55,020	71%
United States	2002	33%	16%	51%	35,000	17,500	53,725	73%
United States	2003	35%	15%	50%	38,000	16,500	55,542	70%
United States	2004	36%	14%	50%	42,000	17,000	58,435	N/A
United States	2005	36%	14%	49%	45,000	17,500	61,230	N/A
United States	2006	33%	14%	53%	41,000	17,000	66,310	N/A
United States	2007	29%	14%	57%	33,000	16,000	63,848	59%
United States	2008	23%	13%	64%	22,000	12,000	61,710	57%
United States	2009	27%	9%	64%	19,000	6,000	45,366	71%
United States	2010	24%	6%	69%	17,000	4,500	48,559	54%
United States	2011	23%	7%	71%	16,500	4,800	51,104	53%
Cuba	2005	22%	43%	35%[1]	225	438	352	N/A
Chile	2006	35%	35%[2]	30%[1]	1,533	1,533	1,314	N/A
Mexico	2006	50%	13%	35%	16,393	4,262	11,475	N/A
China	2006	35%	30%[3]	35%[4]	370,404	317,489	370,404	N/A
Vietnam	2006	20%	N/A	N/A	6,172	N/A	N/A	N/A
Azerbaijan	2006	55%	23%	22%	1,087	455	435	N/A
Israel	2006	50%	17%	33%[1]	1,663	565	1,097	N/A
Czech Republic	2006	20%	45%	35%	883	1,988	1,546	57%
Slovenia	2006	25%	5%	70%[1]	338	68	946	N/A
Serbia and Montenegro	2006	60%	N/A	N/A	1,296	N/A	N/A	N/A
Austria	2006	27%	27%	47%	1,420	1,420	2,485	N/A
France	2006	40%	25%	35%[1]	9,062	5,685	7,768	N/A

Italy	2006	36%	31%	33%[1]	16,579	14,276	15,197	N/A
Germany	2006	37%	29%	34%[1]	10,006	7,842	9,195	N/A
Finland	2006	29%	38%	33%	496	651	565	N/A
Spain	2006	N/A	N/A	45%	N/A	N/A	23,180	N/A
Turkey	2006	66%	17%	17%[1]	23,260	5,824	6,034	N/A
South Africa	2006	60%	25%	15%	7,161	2,984	1,790	N/A

[1] The cement use for the construction of all types of non-residential buildings is not reported. Therefore, the reported cement use in infrastructure projects could also include cement consumption for the construction of some non-residential buildings
[2] Only industrial buildings
[3] Industrial 15% and public facilities 15%
[4] Infrastructure 15% and agriculture 20%

Figure 5 shows the annual per capita residential cement consumption in relation to the residential floorspace area for the United States (total floorspace divided by population). It can be seen, that the cement consumption per capita increases as bigger houses are being built (desire for bigger housing surface area).

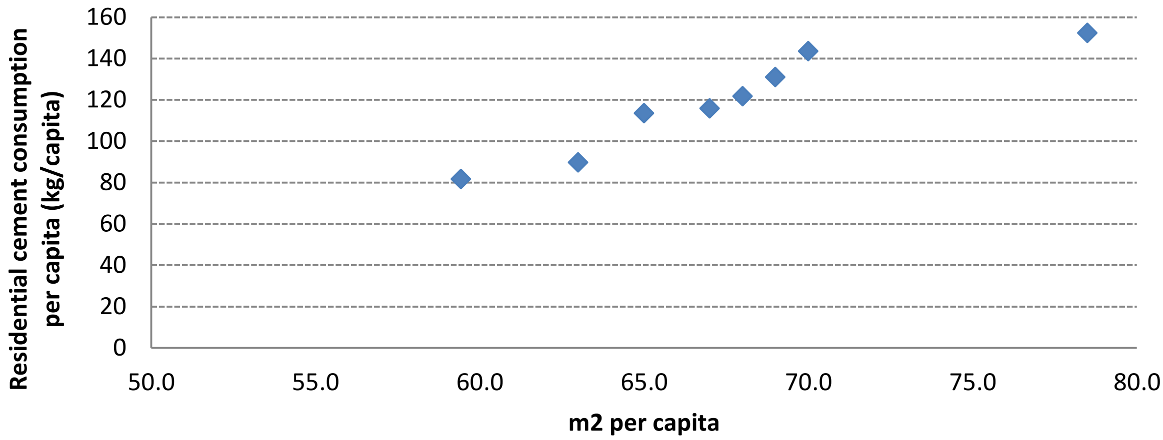

Figure 5 Per capita residential cement consumption and residential floorspace in the United States (period 1998 to 2005)

Based on Table 1 and on information on cement use in the EU countries, the residential cement use is plotted against the average residential floorspace area (see Figure 6). In the case of the EU, cement consumption breakdowns per different construction sector do not taken 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.

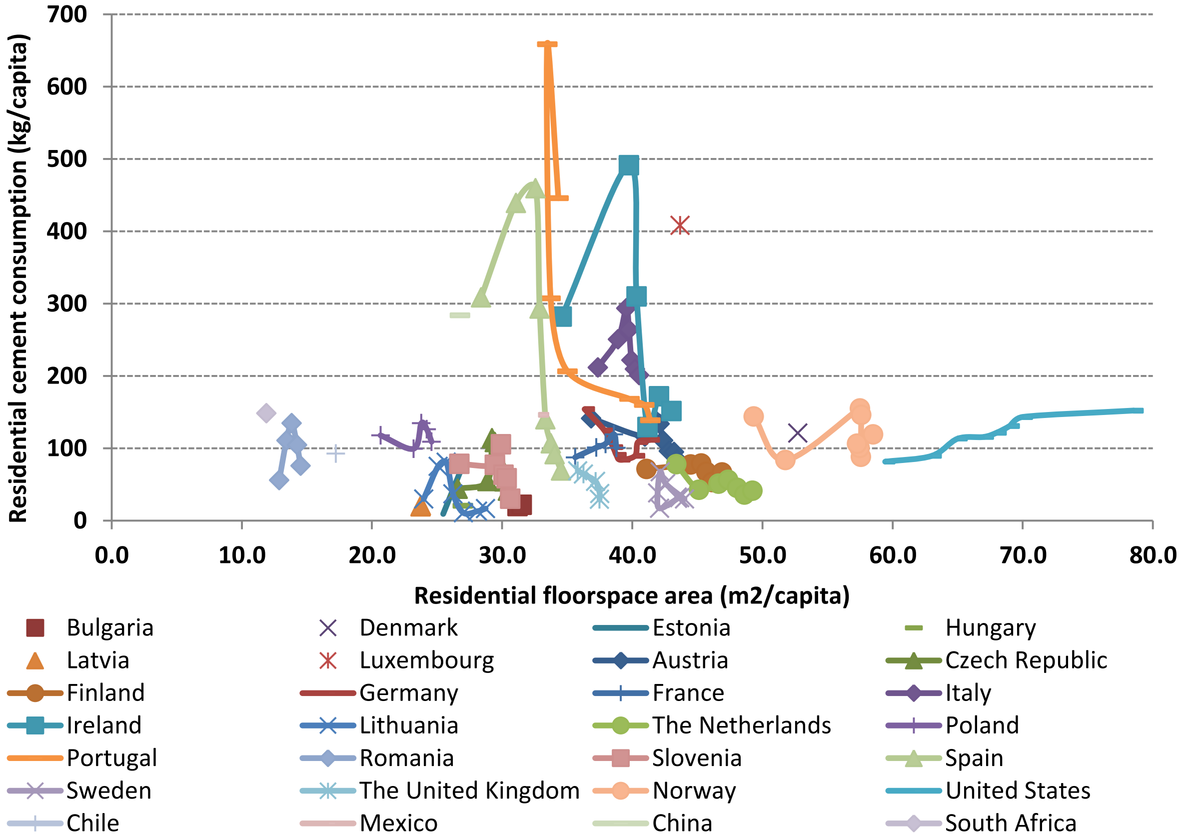

Figure 6 Per capita cement consumption in the residential sector in EU countries (period 2000-2013) and other non-EU (1998-2005)

Sources: CEMBUREAU, 2015; own calculations based on ODYSSEE, 2015

As seen in Figure 6, the U.S. residential floorspace per capita is almost double the floorspace in European countries. The residential floorspace area in the U.S. is one of the largest (76m^2/capita), and then follow Norway (59m^2/capita) and the Netherlands (50m^2/capita). However, the per capita cement consumption in the U.S. is at a similar level. This is mainly due to the fact that in the U.S., while cement is widely used in the construction of residential buildings, wood is another material commonly used. An increasing trend in the per capita cement use can be observed in the early 2000s for many European 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 7 shows the correlation between the non-residential cement consumption and the floorspace developments in the United States within the 1998-2008 period. Figure 8 shows the same correlation while also including the years during the financial crisis.

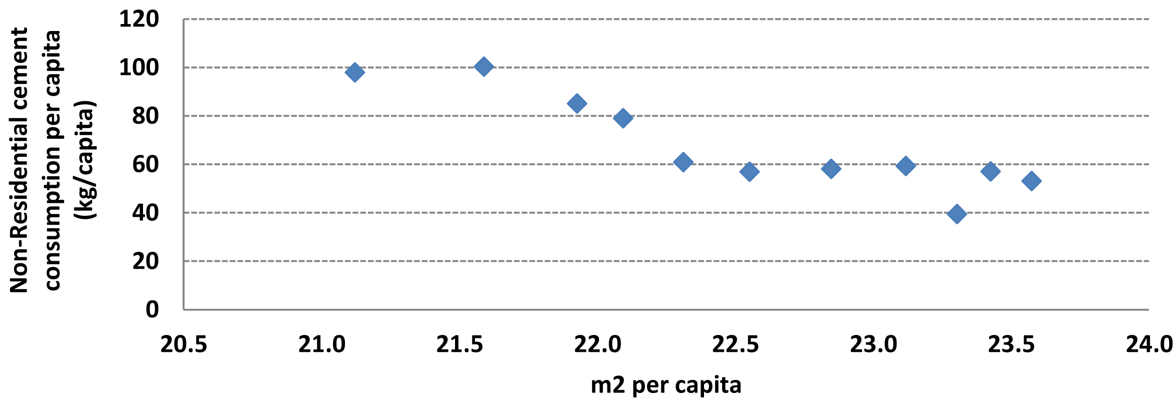

Figure 7 Non-residential cement consumption per capita and non-residential floorspace in the United States (period 1998-2008)

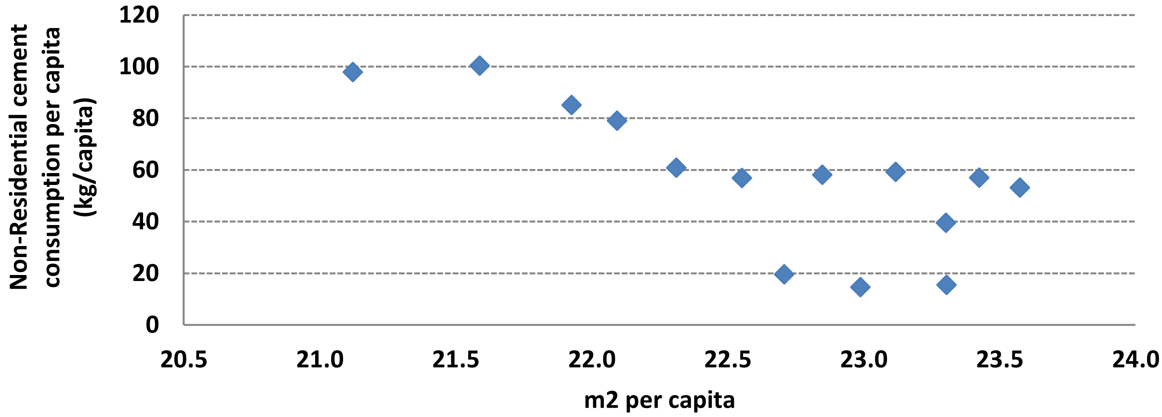

Figure 8 Non-residential cement consumption per capita and non-residential floorspace in the United States (period 1998-2011)

In the above Figures it is shown that the per capita cement consumption decreases with the increase in the non-residential floorspace. Figure 9 shows the cement consumption per surface area in the non-residential sector plotted against the per capita service sector's value added. Although the value added in the service sector increases, the cement use for the construction of non-residential building decreases. The observed trends 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. The decoupling seen in Figure 8 after 2008 could be the result of a decrease in the commissioning of new material intensive projects in combination with the completion of older projects.

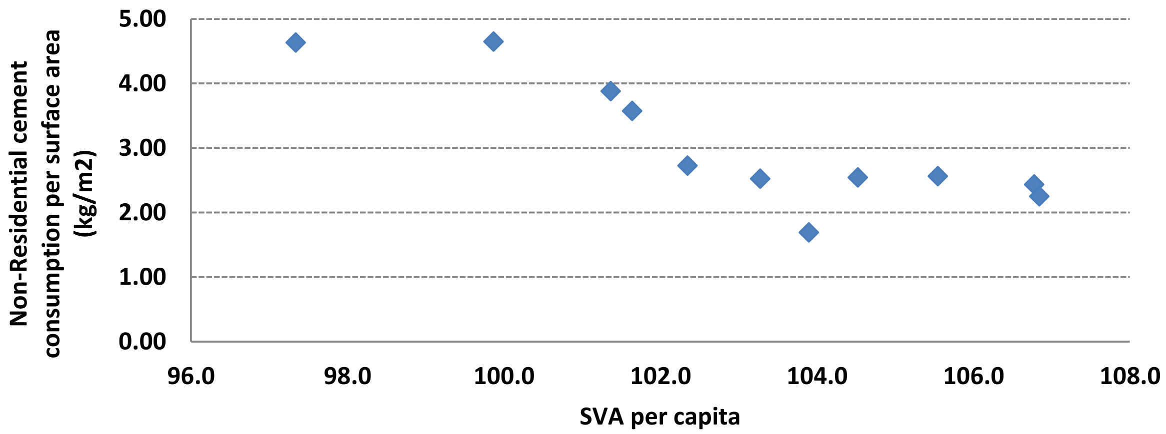

Figure 9 The cement consumption in the non-residential sector and the per capita service sector's value added in the United States (period 1998 to 2008)

Figure 10 shows the correlation between the cement consumption per capita for road construction and the passenger kilometer developments in the United States for the years for which data is available. Figure 11 shows the same correlation while also including the years during the financial crisis. It can be seen that the per capita cement consumption shows an initial increase and after a plateau it decreases. The cement consumption for road/highway construction in the U.S. ranges between 120 and 140 kg/capita. The big reduction in cement use during the crisis could be attributed to the completion of older projects and the fewer projects being commissioned.

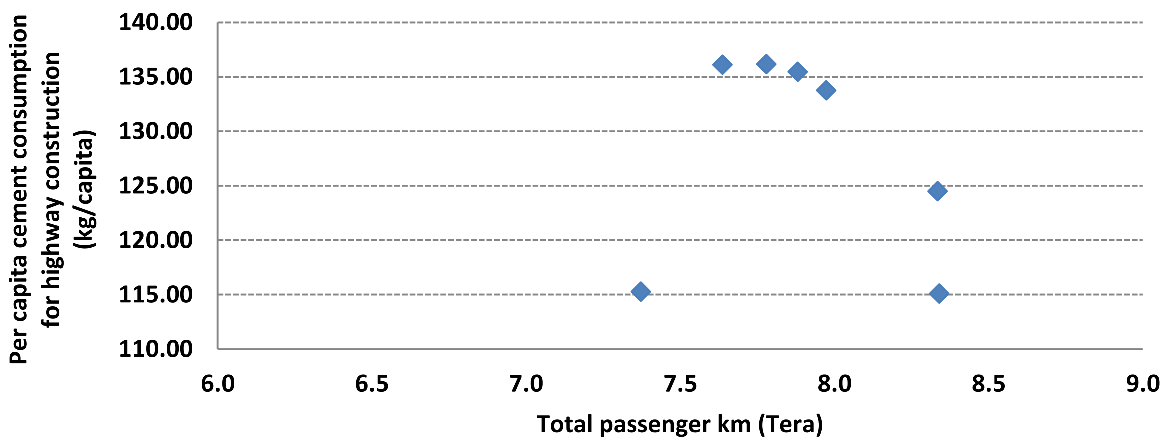

Figure 10 Per capita cement consumption for road/highway construction and km passenger in the United States (1999-2003 and 2007-2008)

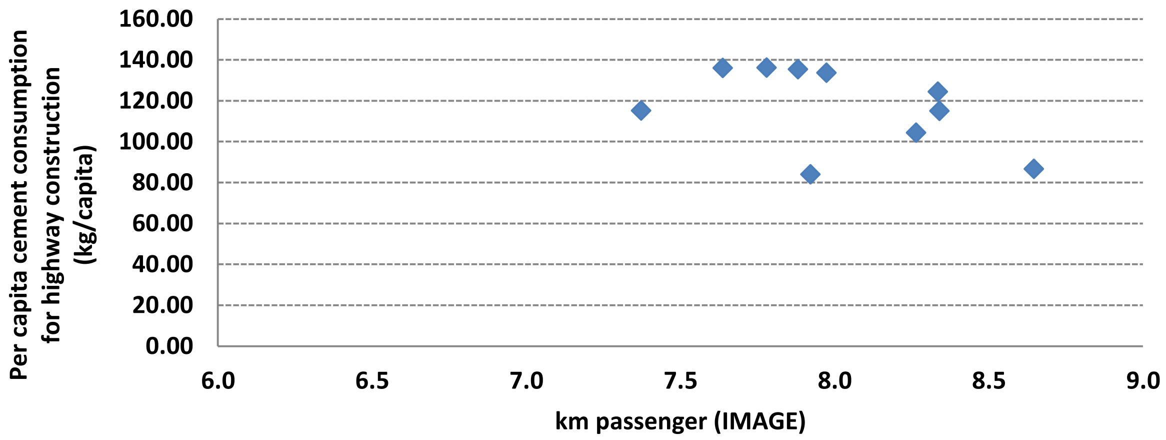

Figure 11 Per capita cement consumption for road/highway construction and km passenger in the United States (1999-2003 and 2007-2011)

The observed relationship between cement consumption in the various construction sectors and the increase in the floorspace or the passenger-km could be used to forecast cement demand. However, the lack of data has complicated finding robust results.

In the above paragraphs it was shown that there is a correlation between cement consumption in the different construction sectors (residential, non-residential and infrastructure) and floorspace or km passenger (Figure 5, Figure 7 and Figure 10). However, there is a big lack of time series data on the cement use per construction activity for most of the countries. The limited data availability poses a big obstacle in estimating a correlation function that can describe in a useful way the correlation between cement use and construction for all regions. Great value would be added if time series data for China (largest cement consumer) and Europe (higher concrete use in construction than the U.S.) were available for the years prior to the financial crisis.

On the other hand, modelling cement production directly with GDP, has the main advantage that there is plenty of data available.

3.1.2 Cement consumption and GDP

The inverted U-shaped curve, that describes the correlation between GDP per capita and material intensity most commonly used in models to forecast the demand for materials, has been widely used to forecast cement consumption. In general, cement demand follows the growth in income per capita. For countries moving towards industrialization cement intensity (t/$) increases following the increase in investments in construction. At a certain income per capita, cement intensity reaches a maximum and then follows a decreasing trend.

Figure 12 shows the historical development of cement production per GDP and GDP per capita for all world regions.

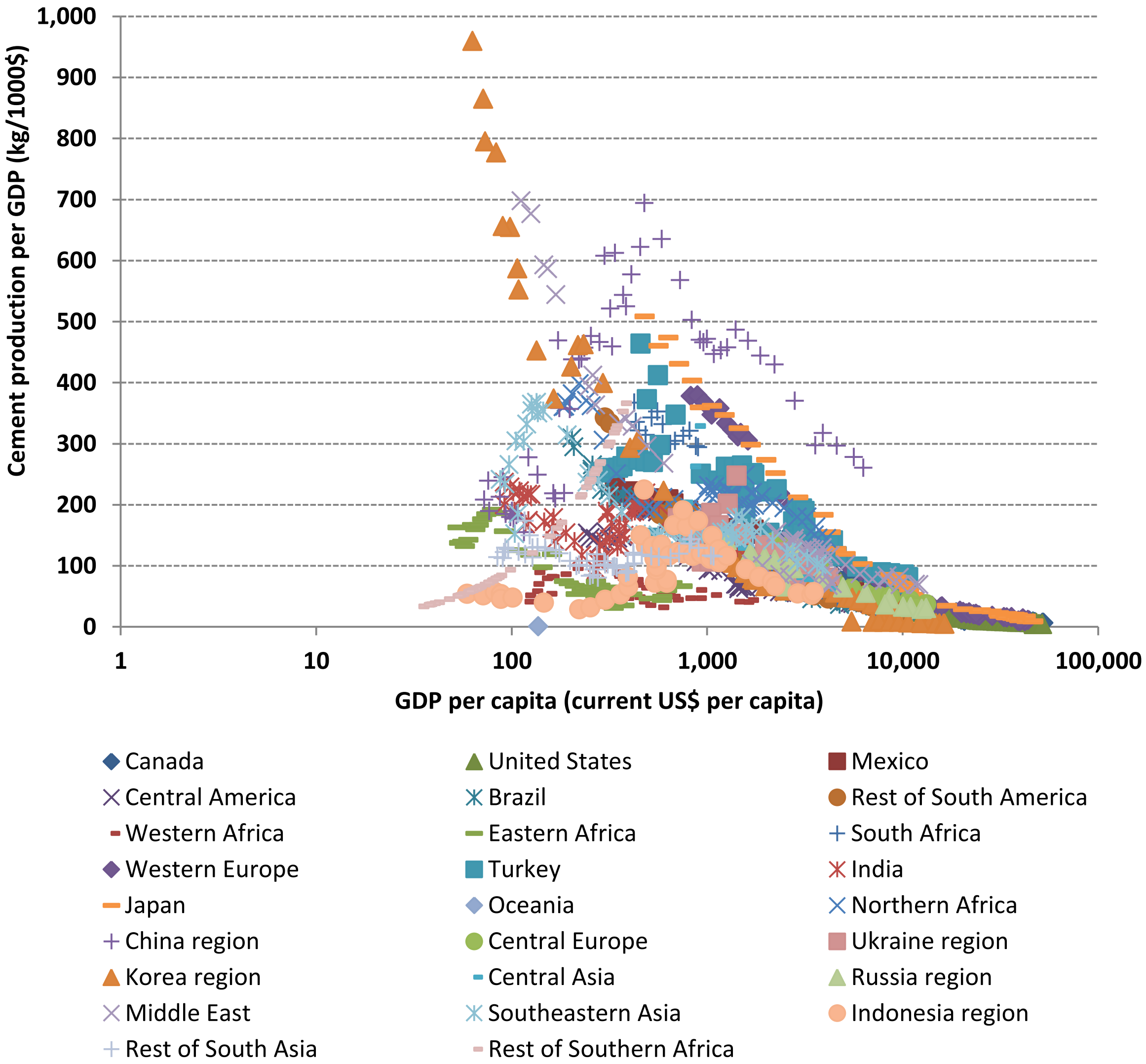

Figure 12 Per GDP production of cement versus the GDP per capita in the various world regions

Bas van Ruijven (NCAR) performed a regression analysis on the relation between per capita consumption of cement and GDP per capita (van Ruijven et al., 2016). This paper evaluated multiple models to identify the best representation of patterns in historic data. The regression analysis was done at the global level, aggregating data to 26 regions as defined for the IMAGE model (Stehfest et al., 2014). From a set of five linear and three non-linear models, exploring different relations between per capita cement consumption, GDP per capita and sometimes time-dependent efficiency improvement, the non-linear inverse model performed better than any other model (see van Ruijven et al. (2016) for details). This model holds the functional form of per capita consumption $C = a*e^{(b/GDPpc)}$, for which the parameters a (487) and b (-3047) are estimated on historical data. These parameters have some physical meaning as well, as a indicated the per capita saturation level of cement consumption an b the income level at which the maximum consumption occurs.

In the IMAGE model van Ruijven et al. (2016) apply this global NLI model and assume that all regions converge towards the globally derived consumption curve by 2060 (Figure 13). Some regions are historically close to this curve, such as India, Western Europe and the USA, while other regions have higher historic consumption, such as China and Korea (). A Gompertz curve was used to smooth out deviations between historic regional data and the global per capita consumption curve.

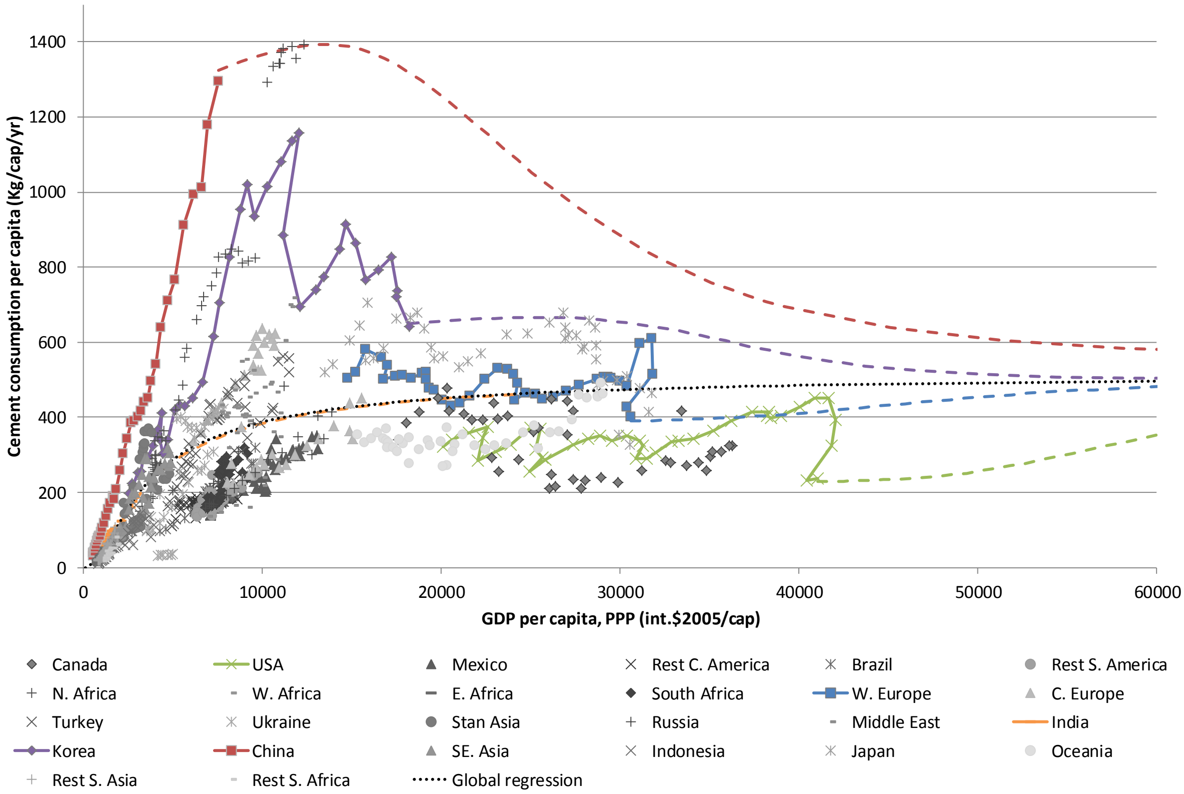

Figure 13: Per capita consumption of cement vs. GDP per capita. Historical data shown for 26 world regions for the period 1970-2010. Five major regions are highlighted: USA, Western Europe, Korea, India and China, each with future projections of per capita cement consumption in dotted lines. The black dotted line represents the global regression.

3.1.3 Cement trade

In 2011, total international cement trade (imports plus exports) accounted for around 7.7% of total cement production (CEMBUREAU, 2013). Imports were significant in Oceania with 6.8 Mtonnes being imported to cover 41% of cement demand. In 2010, cement imports in Australia were lower (3.1 Mtonnes were imported in 2010) and covered 27% of cement demand. In Europe, about 74 Mtonnes of cement were traded (48 Mtonnes were exported and 26 Mtonnes were imported). For more details on cement imports and exports see Table 18 in the Appendix.

In general, cement trade is limited as cement is a product that is costly to transport over land. For the most common cement types, the inland transport radius is not more than 300 km. Cement however, can be transferred economically over large distances by sea (Harder, unknown date). Figure 14 shows the total cement production and consumption volumes in the various world regions.

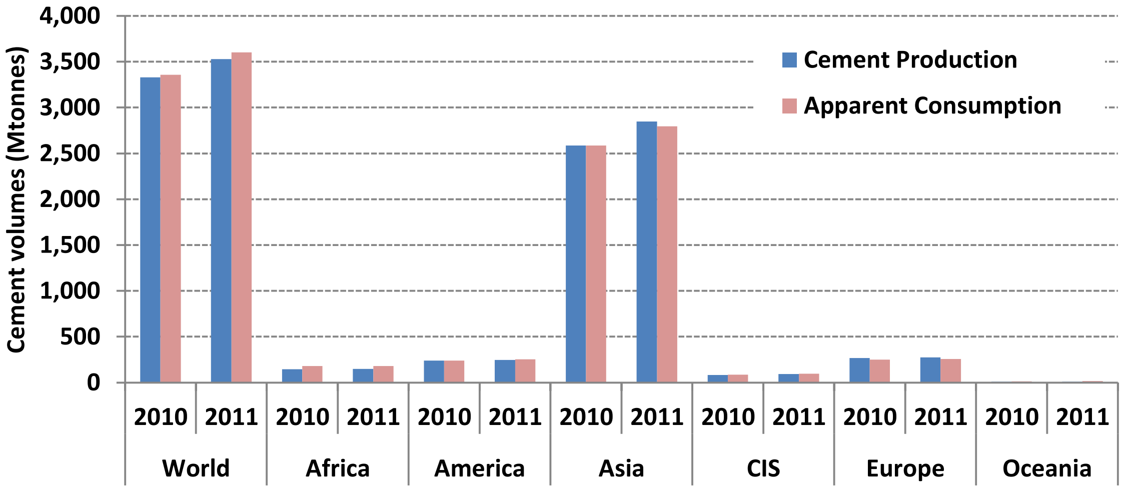

Figure 14 Cement consumption and production in 2010 and 2011 in the different world regions (based on CEMBUREAU, 2013)

As for most regions cement production is broadly equal to cement consumption, models could assume that the total cement demand of the country/region will be satisfied by the local cement production. Another simplified approach could also be to keep the historical export and import ratios constant over time.

3.2. Baseline energy use

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 additives (e.g. slag powder). The most energy intensive step is the calcination of clinker, responsible for the majority of the fuel use (Worrell and Galitsky, 2008).

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

Table 2 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 clinker 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	$kgCO_2/GJ$
$SEC_{el.,t}$	Electricity use for cement making in year t	MJ/tonne cement
$Clinker_{ratio,t}$	The clinker to cement ratio in year t	%

Energy use for clinker making

Based on the moisture content of the raw materials, clinker production can take place in a wet, dry, semi-dry or semi-wet kiln. Although the majority of clinker is produced with the dry process, a large amount of clinker is still produced with the more energy intensive wet process. Figure 15 shows the shares of kiln technologies worldwide (WBCSD data)[3]. Regions with a relatively high share of the wet and the semi-wet processes are the Commonwealth of Independent States (CIS) (80%), Europe 28 (19%), Australia (8%) and the United States (7%) (see Table 3).

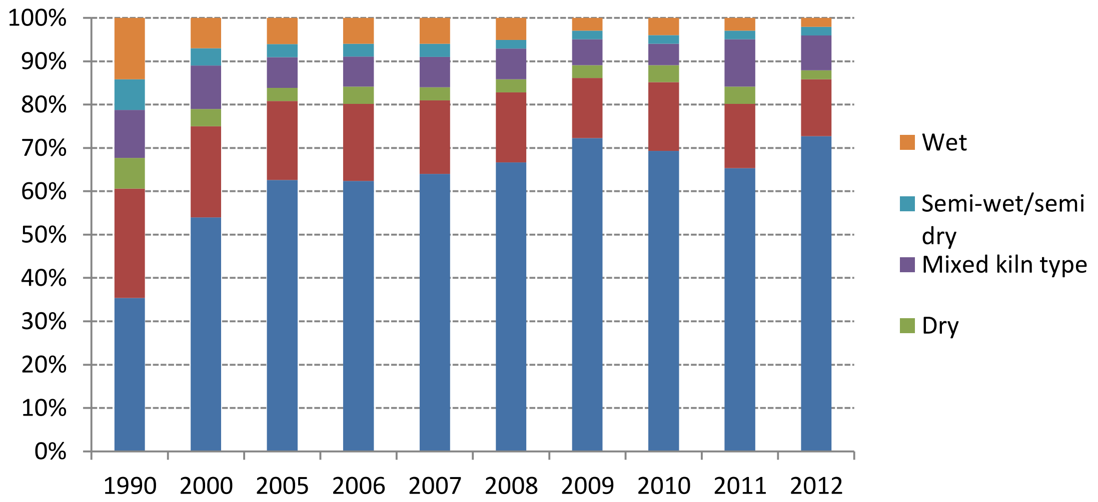

Figure 15 Global shares of clinker production produced with varying kiln types (WBCSD, 2014)

Table 3 Kiln technologies used in the different regions

	2011 Cement Production (ktonnes)[1]	Global share	Dry-process (% of clinker production)	Wet-process (% of clinker production)	Sources
Europe 28			81%	19%	WBCSD, 2014
United States	68,639	1.9%	93%	7%	USGS, 2013

[3] The global coverage of the WBCSD database is limited to 34% of cement production. For some regions the coverage is high (i.e. Europe and North America), while for others it is very low (i.e. China). The coverage can be seen in the Appendix in Figure 24.

Canada	12,001	0.3%	100%	0%	CIEEDAC, 2013
China	2,099,000	58.1%	89%	11%	Zhang et al., unknown date
India	240,000	6.6%	99%	1%	CSI, 2013
Russia	55,600	1.5%	13%	87%	European Union, 2009
Australia	9,100	0.3%	92%	8 %	CIF, 2014
CIS			20%	80%	WBCSD, 2009
Japan	51,291	1.4%	95%	5%	WBCSD, 2009
New Zealand	1,100	0.0%	95%	5%	WBCSD, 2009
Asia			95%	5%	WBCSD, 2009
Brazil	64,093	1.8%	100%	0%	WBCSD, 2014
Latin America			95%	5%	WBCSD, 2009
World	3,610,000				

[1] The clinker production can be estimated based on clinker to cement ratio shares for the specific regions (see Figure 21)

Countries with a high share of the wet process will have a higher average fuel use in clinker making. Table 4 shows the typical energy intensities of the different kiln technologies.

Table 4 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

As a result of the kiln technology type used and the level of energy efficiency, the energy use differs per region with the thermal energy use for clinker production ranging between 3.1 and 5.0 GJ/tonne clinker (see Figure 16). The lowest energy consumption is observed in India where cement capacity increased significantly in recent years and the highest in CIS where they still rely heavily on the wet process.

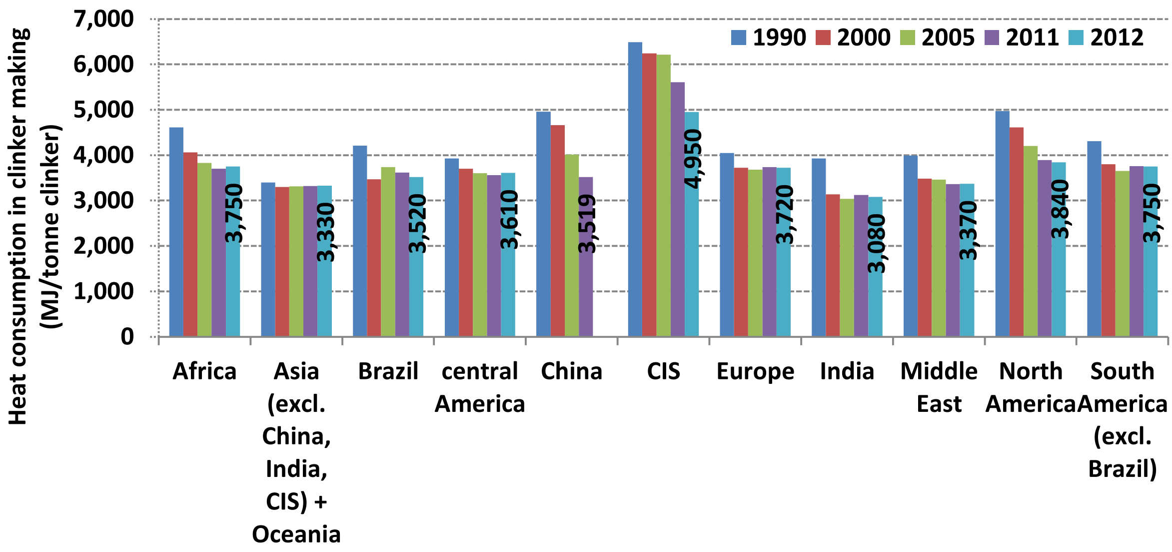

Figure 16 Heat consumption for clinker making (WBSCD, 2014; Xu et al., 2012). Heat use for raw material drying is not included

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 energy use for clinker making in a specific region can be estimated from Eq. (2) when the kiln technology breakdown and the typical fuel and electricity energy intensities are used.

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

Electricity use in cement plants

Most of the energy consumed in a cement plant is in the form of fuel that is used to fire the kiln. 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.

More than 60% of the electricity consumed is used for grinding. The type of the grinding technology used plays a significant role in the plants overall electricity use. Plants employing high pressure roller presses and roller mills are less electricity intensive than plants using ball mills. Table 5 and Table 6 show the typical energy intensities of the various grinding technologies.

Table 5 Electricity use[1] for raw material and cement grinding (Worrell et al., 2013)

Grinding technology	Raw material grinding (kWh/tonne raw material)	Cement grinding (kWh/tonne cement)
Ball mill	19-29	32-37
Horizontal roller mill	7-8	18-21
Vertical roller mill	<10	21-23
Roller presses	15	19-21

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

Table 6 Electricity use[1] for fuel grinding (Worrell et al., 2013)

Grinding technology	Fuel grinding (kWh/tonne coal)
Impact mill	50-66
Tube mill	28-29
Vertical roller mill	15-23

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

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). A more detailed information on the share of the different grinding technologies per world region would enable the estimation of the regional electricity use by using the typical electricity intensities of each technology. However, such information is scarce. Regional information on the different level of total electricity use [also including the electricity use for kiln operation ($E_{el.,kiln}$) seen n Eq.(1)] in cement plants is provided by the WBCSD database.

Based on the WBSCD database, in 2012, the total electricity use ranged between 82 and 126 kWh/tonne cement. The lowest electricity use is observed in India (82 kWh/tonne) and the highest in the North America (126 kWh/tonne) and CIS (121 kWh/tonne) (see Figure 17).

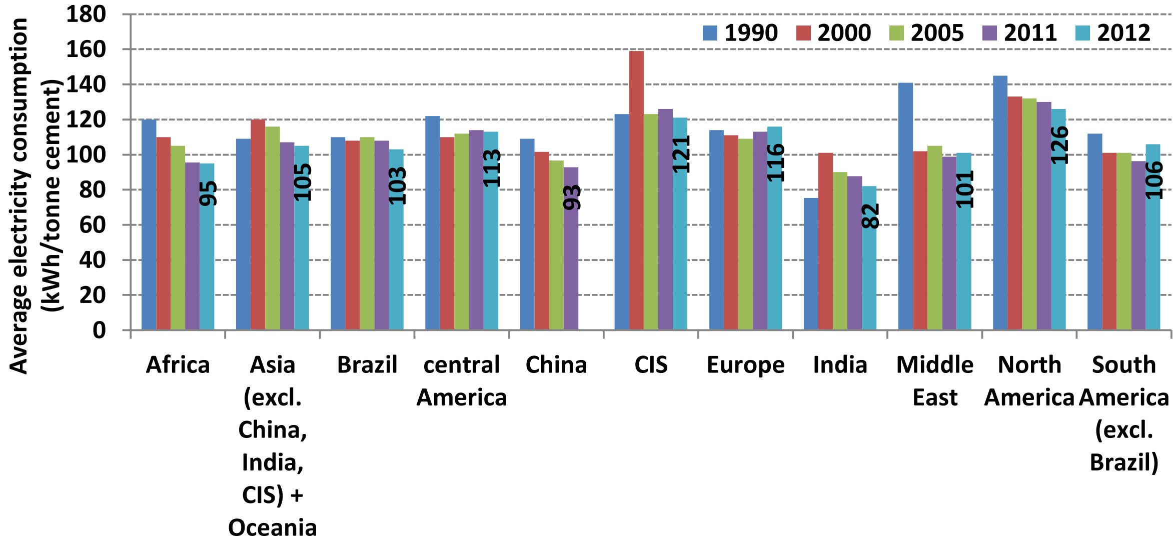

Figure 17 Average electricity consumption for cement making by geographic region (WBCSD, 2014; Xu et al., 2012)

The total energy consumption of cement making in the different world regions can thus be estimated by Eq. (5). As the available data on the electricity use from the WBCSD involve the total electricity use, in this equation, $E_{raw\ material\ prep.,t}$, $E_{el.,kiln,t}$, and $E_{cement\ grinding,t}$, from Eq. (1) is aggregated into $SEC_{total\ el.,t}$.

$$E_{cement,t} = \left(\sum_i Kiln_{ratio,i,t} \times SEC_{thermal,i,t}\right) \times Q_{clinker,t} + SEC_{total\ el.,t} \times Q_{cement,t} \tag{3}$$

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 autonomous energy efficiency improvement occurs due to technological developments. Each new generation of capital goods is likely to be more energy efficient than the previous one. Energy efficiency improvements also occur due to the various policy measures where actors change their behavior, and invest for example into technologies characterized by improved energy efficiencies. In this analysis, both the autonomous and the policy-induced energy efficiency improvements fall under the same definition of energy efficiency improvements.

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). These two rates could thus be used to determine the energy use under a baseline scenario.

3.3. Energy efficiency improvements

A wide variety of measures have been identified able to reduce the energy use and CO_2 emissions in the different process steps in cement manufacture.

Table 7 and Table 8 list energy efficiency improvement measures for cement plants operating the dry process, and Table 9 and Table 10 for cement plants operating the wet process.

Table 7 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]
Raw Materials Preparation				
Mechanical Transport Systems	-	1.2 - 3.5	0.2-5.2	>3 (1)
Improved Pneumatic Systems	-	1.9	N/A	N/A (1)
Improved Raw Mill Blending	0.0-0.02	1.3-4.2	3.5-6.3	>10 (1)
Use of Vertical Roller Mills	-	10.9-12.9	8.0-36.0	>10 (1)

Use of High-Pressure Roller Presses	-	20.0-20.8	7.60	7.0-8.0 (1)
High Efficiency Classifiers	-	4.6-6.3	3.10	>10 (1)
Separate Raw Material Grinding	-	1.0-1.4	5.8-23	>10 (1)
Raw Meal Process Control	-	1.5-1.8	N/A	1
Fuel Preparation	-	0.8-2.4	N/A	N/A (1)
Clinker Making				
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 to6)	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 8 Energy efficiency measures for cement making – dry process cement plants (Worrell et al., 2013)

Energy Efficiency Measure	Specific Fuel Savings (GJ/tonne cement)	Specific Electricity Savings (kWh/tonne cement)	Investment Cost ($/tonne cement)	Estimated Payback Period (years)[1]
Finish Grinding				
Energy Management and Process Control	-	1.6-8.5		<2

Vertical Roller Mills	-	9.0-20	7-39	>8 (1)
Horizontal Roller Mills	-	15.6	16	>10 (1)
High-Pressure Roller Presses - pregrinding	-	5.00-10.00	6	>10 (1)
High-Pressure Roller Presses - finish grinding	-	11.00-25.00	16.00	>10 (1)
Improved Grinding Media	-	1.8	2.5	>10 (1)
High-Efficiency Classifiers	-	1.70-6.00	1.5-3.0	>5 (1)
Plant Wide Measures				
Preventative Maintenance	0.04	0.00-5.00	N/A	<1
High Efficiency Motors	-	0.00-5.00	N/A	<1
Adjustable Speed Drives	-	5.50-9.00	0.2-0.9	1.00-3.00
Optimization of Compressed Air Systems	-	0.00-2.00	N/A	<3
High Efficiency Fans	-	0.9	N/A	N/A
Efficient Lighting	-	0.00-0.50	N/A	N/A

[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 9 Energy efficiency measures for clinker making – wet 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]
Raw Materials Preparation				
Slurry Blending and Homogenizing	-	0.1-0.8	N/A	<3
Wash Mills with Closed Circuit Classifier	-	9.2-12.9	N/A	>10 (1)
High Efficiency Classifiers	-	4.6-6.3	N/A	>10 (1)
Fuel Preparation	-	1.0-3.0	N/A	N/A (1)
Clinker Making				
Energy Management and Control Systems	0.2-0.3	0-4.9	0.2-0.3	<1
Kiln Combustion System Improvements	0.1-0.7	-	1.00	<3 (1)
Mineralized Clinker	0-0.3	0- -1.0	N/A	N/A
Indirect Firing	0.2	0- -0.6	6.7-9.3	>10 (1)
Oxygen Enrichment	0.0-0.3	(-)10- (-)35	3.5-6.9	N/A(1)

Mixing Air Technology	0.30	(-) 0.03	1.2	1 (1)
Seal Replacement	0.03	-		<1
Kiln Shell Heat Loss Reduction	0.1-0.6	-	0.25	<1
Refractories	0.06	-	0.7	4
Conversion to Grate Cooler	0.5	(-)3.00- (-)6.00	10-14	9.00-12.00
Optimize Grate Cooler	0.05-0.16	0.0- (-)2.0	0.7-2.1	2.00-7.00
Conversion to Semi-Dry Process Kiln	1.2-1.6	(-) 5.5- - 7.7	N/A	>10 (1)
Conversion to Semi-Wet Process Kiln	0.8-1.2	-4.4	1.8-4.0	1.00-3.00
Conversion to Dry precalciner Kiln	2.2-3.4	-10	55	>7 (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 10 Energy efficiency measures for cement making – wet process cement plants (Worrell et al., 2013)

Energy Efficiency Measure	**Specific Fuel Savings (GJ/tonne cement)**	**Specific Electricity Savings (kWh/tonne cement)**	**Investment Cost ($/tonne cement)**	**Estimated Payback Period (years)[1]**
Finish Grinding				
Energy Management and Process Control	-	1.6-8.5		<2
Vertical Roller Mills	-	9.0-20	7-39	>8 (1)
Horizontal Roller Mills	-	15.6	16	>10 (1)
High-Pressure Roller Presses - pregrinding	-	5.00-10.00	6	>10 (1)
High-Pressure Roller Presses - finish grinding	-	11.00-25.00	16.00	>10 (1)
Improved Grinding Media	-	1.8	2.5	>10 (1)
High-Efficiency Classifiers	-	1.70-6.00	1.5-3.0	>5 (1)
Plant Wide Measures				
Preventative Maintenance	0.04	0.00-5.00	N/A	<1
High Efficiency Motors	-	0.00-5.00	N/A	<1
Adjustable Speed Drives	-	5.50-9.00	0.2-0.9	1.00-3.00
Optimization of Compressed Air Systems	-	0.00-5.00	N/A	<3
High Efficiency Fans	-	0.9	N/A	N/A
Efficient Lighting	-	0.00-0.50	N/A	N/A

[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.

There are several ways with which energy efficiency improvements could be incorporated into the models. Some of them are:

- *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 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 $C_{CO2\text{-}eq}$ can be determined with the use of Eq.4 and Eq.5, respectively.

$$CCE = \frac{Annualized\ investment\ cost + Annual\ O\&M\ costs - Annual\ Financial\ benefits\ from\ energy\ savings}{Annual\ energy\ savings} \quad (4)$$

$$C_{CO2} = \frac{Annualized\ investment\ cost + Annual\ O\&M\ costs - Annual\ Financial\ benefits\ from\ energy\ savings}{Annual\ GHG\ emission\ savings} \quad (5)$$

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 can be determined) become cost-effective can be determined.

- *Payback period*

The payback period (PBP) could be estimated for every measure. All measures can then be ranked based on their PBP. The measures with the lowest PBP will be implemented first.

- *Step functions*

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 (Figure 18) and assess how much the energy consumption can decrease and at what cost.

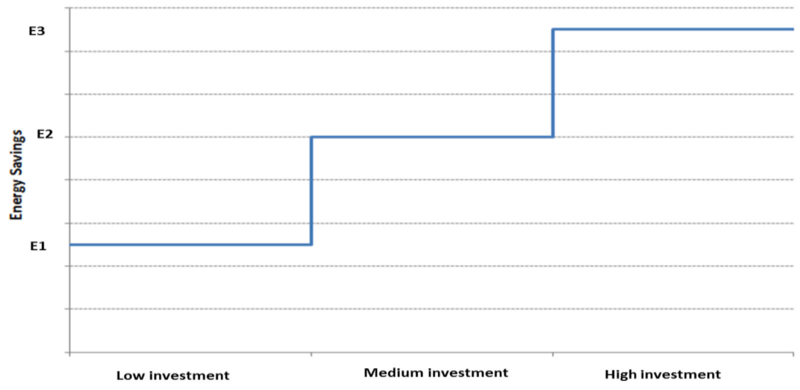

Figure 18 Energy saving potentials based on the investment cost

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). Table 11 and

Table 12 show the aggregated based on the investment costs energy efficiency improvement opportunities. 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.

Table 11 Energy efficiency improvements in clinker making clustered based on the investment costs (dry process)

Energy Efficiency Measures	Specific Fuel Savings (GJ/tonne clinker)	Specific Electricity Savings (kWh/tonne clinker)	Investment Cost ($/tonne clinker)
Low Investment Measures	0.4-1	1.5-6.7	1.7-1.8
Medium Investment Measures	0.2-0.6	-0.8-3.5	2.9-9.3
High Investment Measures	1.3-1.6	41-54	72-108

Table 12 Energy efficiency improvements in cement making clustered based on the investment costs (dry process)

Energy Efficiency Measure	Specific Fuel Savings (GJ/tonne cement)	Specific Electricity Savings (kWh/tonne cement)	Investment Cost ($/tonne cement)
Low Investment Measures	0.04	8-31	1.40
Medium Investment Measures	-	1.7-6	1.5-3
High Investment Measures	-	18-37	~25

Detailed information on the current level of penetration of the different technologies on a country level is not available (except for the information available on the type of cement kilns “wet” or “dry” used, see Table 3). The implementation rates of the energy efficiency improving measures will vary per region depending on the current level of energy efficiency and can be estimated based on the technical energy savings potentials from the wide implementation of Best Available Technologies (BATs).

Dry kilns equipped with a precalciner and several preheater stages (5 to 6), are currently considered best available technology, and can have under optimal conditions a fuel consumption of about 2.9-3.3 GJ/tonne clinker (IPTS/EC, 2010). Concerning raw material and finish grinding, current state-of-the-art techniques use roller presses and vertical roller mills. The electricity requirements will mainly depend on raw material hardness, moisture content and the type and amount of additives used. Best practice electricity use for cement making is based on Worrell et al. (2008) for cement with 65% Blast Furnace Slag (BFS). Figure 19 shows the technical fuel and electricity savings potentials from BAT implementation.

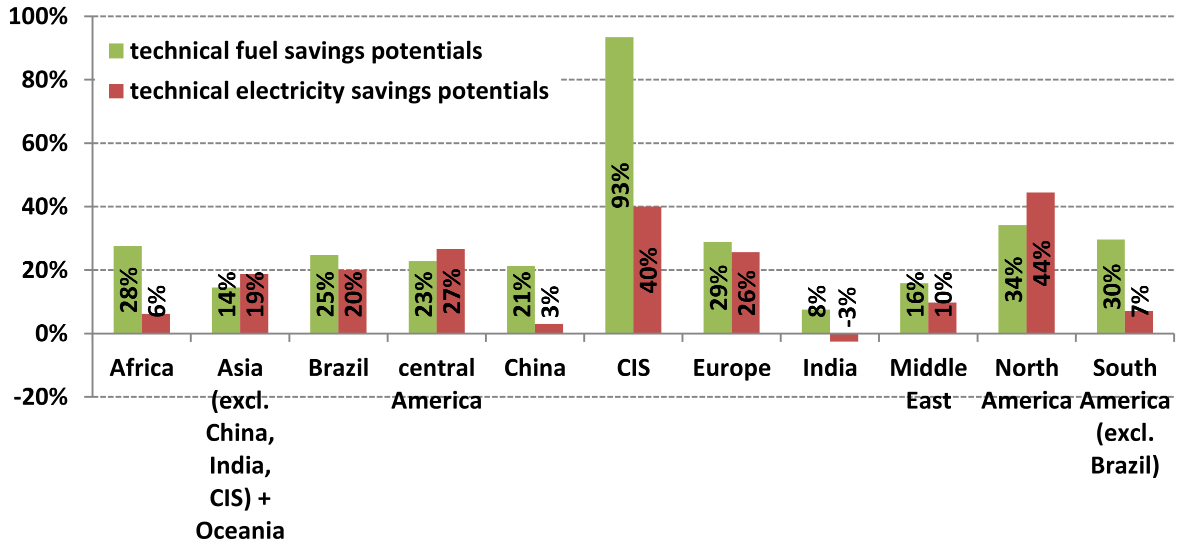

Figure 19 Estimated technical energy savings potentials from wide BAT adoption

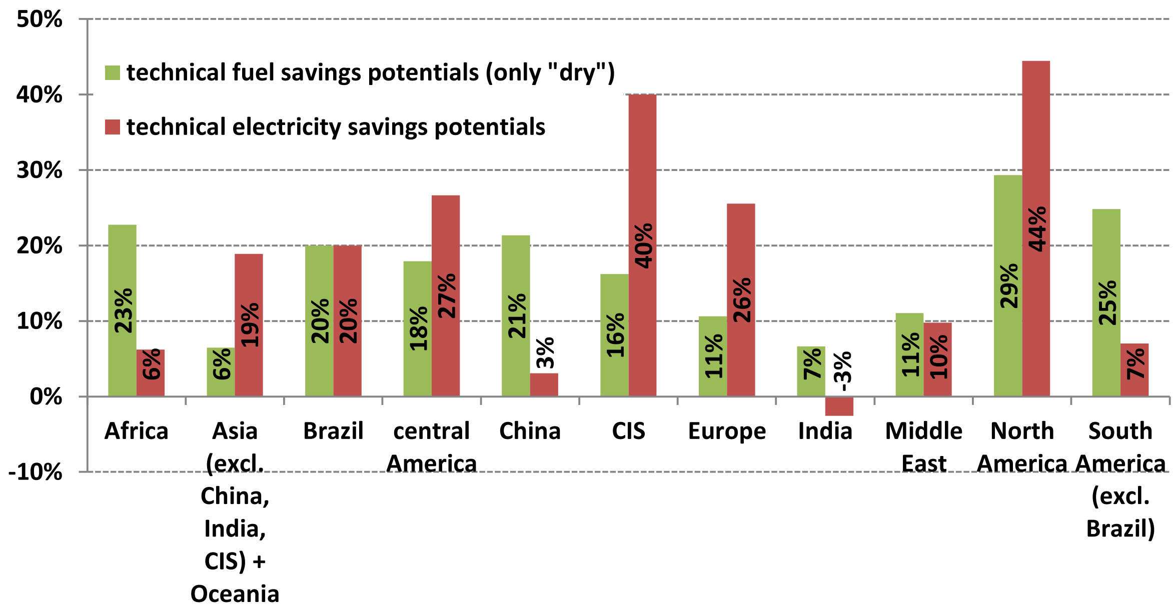

Figure 20 Estimated technical energy savings potentials from wide BAT adoption (dry process plants)

Figure 20 shows the estimated technical fuel and electricity savings potentials for dry plants. To estimate these potentials we considered that all wet plants dropped to BAT levels by adopting state-of-the-art dry cement kilns with preheaters and precalciners[4].

3.4. Baseline CO_2 emissions

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.

$$CO_{2,total,t} = CO_{2-fuel,t} + CO_{2-process,t} + CO_{2-el.,t} = \sum_j (Fuel_{ratio,j,t} \times CEF_{fuel,j} \times SEC_{thermal,t}) \times Q_{cement,t} + \sum_i (CEF_{el.,t} \times \times SEC_{el.,t}) \times Q_{cement,t} + 0.5262 \times Clinker_{ratio,t} \times Q_{cement,t} \quad (6)$$

Data on linker production is not reported on a country or a regional level. However, clinker production can be estimated by multiplying the reported cement production with the regional clinker to cement ratios seen in Figure 21. 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.

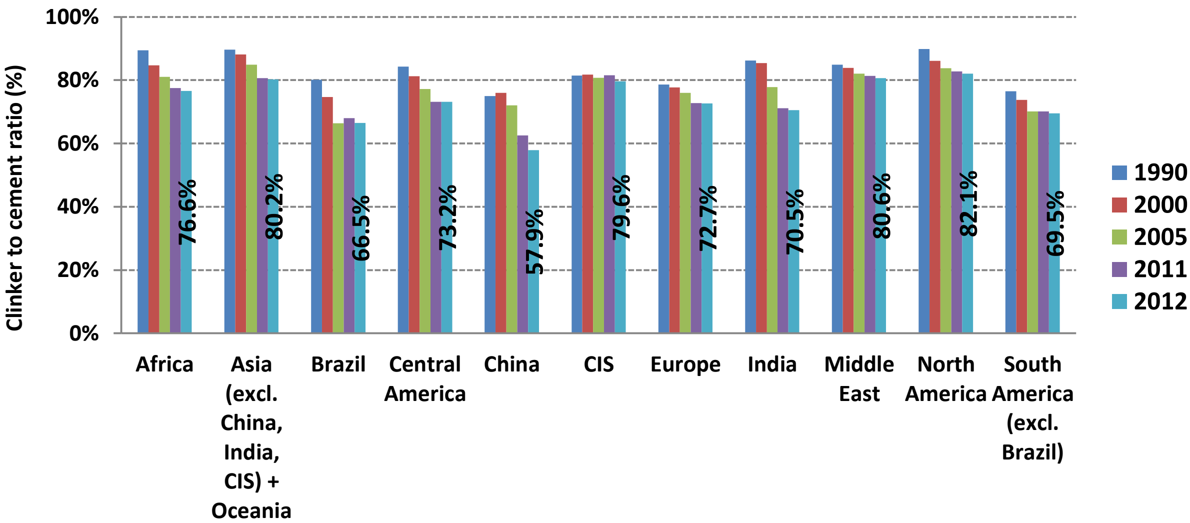

Figure 21 Clinker to cement ratios in the various world regions (WBCSD, 2014; Xu et al., 2012; Zhang et al., unknown date)

Figure 22 shows the different types of fuels used in the cement industry. In Europe, around 45% is comprised by alternative fuels such as waste and biomass.

[4] For the estimation we considered that the energy use in wet plants was reduced by 2,800 MJ/tonne clinker (that is 5,700 MJ/tonne for the typical fuel use in wet plants minus 2,900 MJ/tonne in state-of-the-art dry plants). The share of the clinker produced with the wet process can be found in Table 3. Due to the lack of information, it was assumed that the share of wet plants on the overall clinker production in Africa, Central America, Brazil and Middle East is low, equal to 5%.

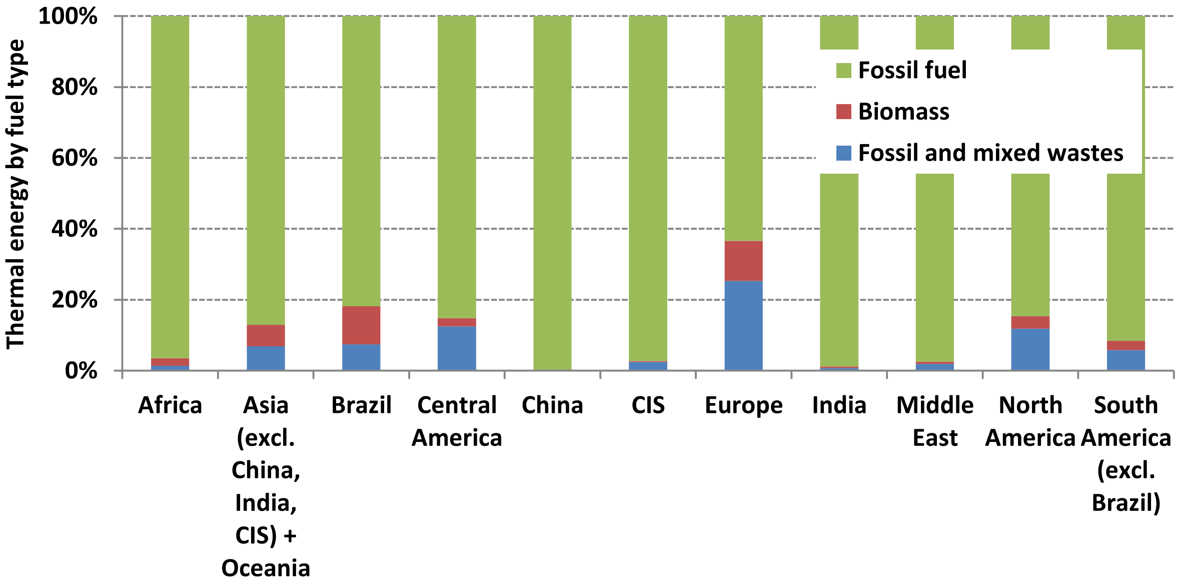

Figure 22 Thermal energy use for clinker making by fuel type (WBCSD, 2014)

3.5. Clinker substitution

The adoption of measures that can reduce the clinker content in cement will not only improve the energy efficiency and limit 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). Table 13 shows the composition of different cement types and the maximum amount of additives that can be used.

Table 13 Typical composition of different cement types (IPTS/EC, 2010)

<table>
<tr><th></th><th>Portland cement</th><th>Portland-composite cements</th><th>Blast furnace cement</th><th>Pozzolanic cement</th><th>Composite cement</th></tr>
<tr><td>Clinker</td><td>95-100%</td><td>65-94%</td><td>5-64%</td><td>45-89%</td><td>20-64%</td></tr>
<tr><td>Blast furnace slag</td><td>-</td><td rowspan="3">6-35%</td><td>36-95%</td><td>-</td><td>18-50%</td></tr>
<tr><td>Fly ash</td><td>-</td><td>-</td><td rowspan="3">11-55%</td><td rowspan="2">18-50%</td></tr>
<tr><td>Pozzolana</td><td>-</td><td>-</td></tr>
<tr><td>Silica fume</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Other additives (e.g. gypsum)</td><td>0-5%</td><td>0-5%</td><td>0-5%</td><td>0-5%</td><td>0-5%</td></tr>
</table>

The production of blended cements involves the intergrinding of clinker with one or more additives. The intergrinding of one tonne of additives will offset the environmental impact (NOx, SO_2, CO_2, PM and other emissions) of producing one tonne of Portland cement (about 0.95 tonnes of clinker) (Staudt, 2009).

The use of blended cements is very common in Europe. About 12% of the cement consumed in Europe is blast furnace and pozzolanic cements, while portland composite cement accounts for an additional 59% (IPTS/EC, 2010). In Europe, a common standard has been developed for 25 types of cement (using different compositions for different applications). The European standard allows wider applications of additives when compared to other countries, such as the U.S., where the use of blended cements is limited. Figure 23 shows the share of additives use in cement manufacture in the different regions. Regions with the highest additive content in cement are Brazil (32%), South America (excl. Brazil) (29%), India (28%) and Central America (26%).

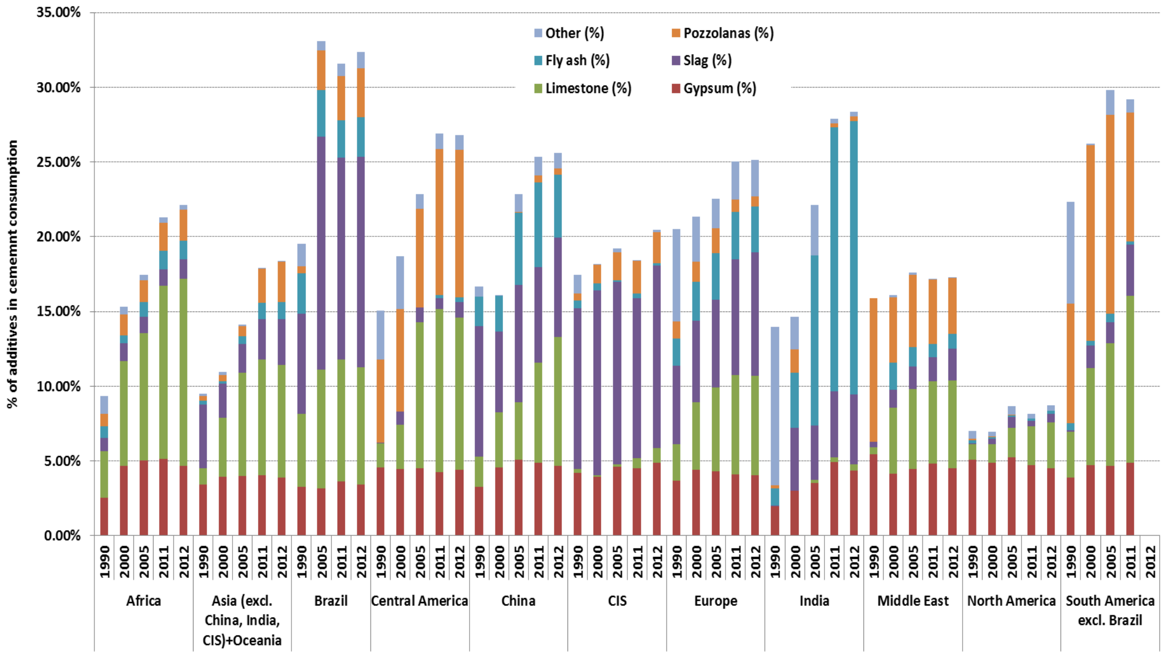

Figure 23 Weighted average of additives content in cement per region (WBCSD, 2014)

Note: According to the WBCSD (2014), in 2012, the additive content in cement in North America, was equal to 9%. However, this percentage is considerably lower than anticipated as according to the same source, the clinker to cement ratio in 2012 was 82% (see Figure 21).

Table 14 and Table 15 show the measures that could decrease the clinker to cement ratio along with the fuel savings potentials and representative for the U.S. industry. Increasing the use of clinker substitutes in cement will result in higher electricity use for cement grinding.

Table 14 Material efficiency improvements – dry process plants (based on Worrell et al., 2013)

Energy Efficiency Measure	Specific Fuel Savings (GJ/tonne cement)[1]	Specific Electricity Savings (kWh/tonne cement)[1]	Investment Cost ($/tonne cement)[1]	Estimated Payback Period (years)[1]
Product Change				
Blended Cement	1.0[2]	-15.00	0.7-5.9	0.50-3.00
Limestone Portland Cement	0.2	3.0	N/A	<1
Feedstock Change				
Use of Steel Slag in Clinker (CemStar) (10% substitution)	0.2	-	0.7-0.8	1.00-2.00
Use of Fly Ash, Blast Furnace Slag in Clinker (15% substitution)	0.3	0.00 - (-)1.70		<7.00 (1)

Use of Cement Kiln Dust in Clinker	0.1	-0.9	0.1	<2
Use of Calcareous Oil Shale in Clinker (8% oil shale)	0.1	-	0.1	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.
[2] Estimated for a 27% decrease of the clinker to cement ratio (from 89% U.S. average in 2009, to 65%). The fuel savings increase almost linearly with the increase in the BFS use. The energy savings will be equal to the fuel use for cement making in the base case (GJ/tonne cement) minus the fuel use for clinker making in the base case (GJ/tonne clinker) multiplied by the new clinker to cement ratio (%). When BFS is used, about 0.09 GJ/tonne cement of fuel are needed for drying while 0.2 GJ/tonne are saved from bypassing (for more details see Worrell et al., 2013).

Table 15 Material efficiency improvements – wet process plants (based on Worrell et al., 2013)

Energy Efficiency Measure	Specific Fuel Savings (GJ/tonne cement)[1]	Specific Electricity Savings (kWh/tonne cement)[1]	Investment Cost ($/tonne cement)[1]	Estimated Payback Period (years)[1]
Product Change				
Blended Cement	1.60	-15.00	0.7-5.9	0.50-2.00
Limestone Portland Cement	0.30	3.00	N/A	<1
Feedstock Change				
Use of Steel Slag in Clinker (CemStar)	0.2	-	0.7-0.8	1.00-2.00
Use of Fly Ash, Blast Furnace Slag in Clinker	0.3	0.00 - (-)1.70		<7.00 (1)
Use of Calcareous Oil Shale in Clinker	0.1	-	0.1	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.

The energy savings from increasing the level of use of supplementary cementitious materials (i.e. decreasing the clinker to cement ratio) will vary per country/region as they are dependent on the current level of fuel use for clinker making and the average clinker to cement ratio. Table 16 shows the regional energy savings from decreasing the clinker to cement ratio in all regions to 65%.

Table 16 Energy savings from decreasing the clinker to cement ratio to 65%

	Energy savings (MJ/tonne cement)	
	2011	**2012**
Africa	463	435
Asia (excl. China, India, CIS) + Oceania	518	506
Brazil	109	53
Central America	292	296
China	0[1]	-
CIS	931	723
Europe	292	286
India	190	169
Middle East	551	526
North America	692	657

South America (excl. Brazil)	192	169

[1] The energy savings in China are zero as the clinker to cement ratio in 2011 was 62.5% (less than 65%)

To calculate the energy savings from the adoption of lower clinker to cement ratios in each region use Eq.(7):

$$Energy\ savings = SEC_{thermal,t} \times Clinker_{ratio,t} - SEC_{thermal,t} \times Clinker_{New\ Ratio} \quad (7)$$

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 (ECRA, 2009):

- Availability of supplementary cementitious materials
- Price of clinker substitutes
- National standards
- Market acceptance
- Cement properties

Although granulated blast furnace slag, fly ash and pozzolanas are materials that are widely available, their regional availability varies widely. The availability of granulated blast furnace slag (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, 2013b).

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. 8).

$$Clinker_{ratio,t} = Clinker_{ratio,Portland} - Limestone_{ratio} - \frac{Q_{fly\ ash,t}}{Q_{cement,t}} - \frac{Q_{BFS,t}}{Q_{cement,t}} - \frac{Q_{pozzolanas,t}}{Q_{cement,t}} \quad (8)$$

Variable	Definition	Unit
$Q_{cement,t}$	Total cement output in year t	Mtonnes cement
$Q_{fly\ ash,t}$	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%)	%

3.6. Emerging technologies

New technologies that can transform the cement industry and substantially decrease the thermal intensity of the clinker making process are currently not in sight. An innovative way of reducing the CO_2 emissions in the cement industry is with the use of Carbon Capture and Storage (CCS). CCS technologies that are considered appropriate for clinker making, although still far from being implemented, are the (ECRA, 2009):

a) Post combustion capture. In which, the CO_2 is separated from the flue gases. No major process changes are needed therefore this CCS technology can be also implemented as a retrofit.

b) Oxyfuel technology. The use of oxygen instead of air in the kilns would require many modifications; this technology is therefore considered very costly for retrofitting. Partial oxyfuel operation (only the precalciner and the kiln operating under oxyfuel conditions) could be considered as a retrofit due to the fewer needed modifications and the smaller product changes. In such a case, carbon capture efficiency would be lower, 60% instead of 85% achieved with total oxyfuel operation.

Estimating the future implementation of CCS is very hard. The captured CO_2 will need to be transferred to a storage site through a CO_2 transport infrastructure. This means that those cement plants located far away from a storage site and those plants not connected to the grid are not CCS candidates, limiting the practical potential for CCS adoption. In addition, due the high investment costs (see Table 17) CCS is not considered applicable in kilns with a capacity of less than 4000-5000tonnes per day.

Table 17 Cost estimations and operational changes for CCS implementation in new cement plants (ECRA, 2009).

CCS technologies	CO_2 reduction ($kgCO_2$/tonne clinker)	Specific Fuel Increase (MJ/tonne clinker)	Specific Electricity Increase (kWh/tonne clinker)	Investment Cost (2007€/tonne clinker)[1,2]
Post-combustion (absorption tech.)	550-870 (direct) & 60-80 (indirect)	90-100	110-115	165-180 (in 2030) 135-150 (in 2050)
Oxyfuel combustion	740 (direct) & 25-60 (indirect)	1,000-3,500	50-90	50-150 (in 2030) 40-125 (in 2050)

[1] Investment costs estimated for a 2 million tonne annual clinker capacity.
[2] Investment costs for CO_2 transport and storage are not included.

According to IEA (2010) the investment costs for a greenfield cement plant when adopting CCS will increase from €263 per tonne cement for a conventional plant to €558 when the post-combustion technology is used and to €327 when the oxyfuel technology is used.

4. Appendix

Table 18 Cement imports and exports in the various world regions (based on CEMBUREAU, 2013)

	Variable	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
World	Cement Production	1,727,278	1,841,785	2,019,558	2,185,356	2,351,981	2,615,176	2,811,547	2,842,678	3,028,164	3,330,210	3,528,789
	Total Exports	135,162	134,821	147,638	162,138	185,219	198,553	192,339	177,041	156,520	174,797	152,173
	Clinker Exports	35,701	38,747	43,682	47,482	53,840	57,728	64,476	54,863	44,562	46,788	45,554
	Total Imports	131,072	128,053	134,656	147,926	168,982	178,474	160,341	154,443	123,669	142,974	118,346
	Apparent Consumption	1,725,256	1,837,460	2,015,680	2,181,764	2,337,471	2,593,121	2,789,303	2,839,229	3,035,295	3,357,442	3,602,707
Africa	Cement Production	75,038	77,092	85,892	90,492	103,675	114,243	122,262	132,682	142,132	144,586	147,418
	Total Exports	4,494	7,891	16,737	22,890	20,756	17,180	14,620	10,636	10,542	8,120	10,026
	Clinker Exports	545	931	4,645	7,623	5,870	3,707	3,252	756	269	386	960
	Total Imports	23,087	22,461	23,986	23,217	24,927	25,083	21,479	32,243	28,387	34,053	17,697
	Apparent Consumption	90,042	90,464	98,785	103,149	115,236	126,983	138,375	147,962	167,109	181,852	182,200
America	Cement Production	218,123	217,067	218,065	231,654	247,119	257,263	264,180	257,296	226,351	238,394	247,637
	Total Exports	15,351	15,614	16,547	17,123	18,021	16,877	16,480	12,839	10,473	9,876	10,412
	Clinker Exports	2,463	2,960	3,258	2,953	2,986	2,229	2,351	2,612	1,884	1,282	1,500
	Total Imports	32,836	30,686	30,595	34,359	40,495	41,832	29,415	18,798	13,880	15,379	18,468
	Apparent Consumption	235,276	230,205	232,330	244,223	261,031	273,706	271,546	259,585	231,332	239,740	252,812
Asia	Cement Production	1,113,495	1,211,769	1,364,209	1,488,517	1,608,911	1,817,732	1,981,072	2,031,071	2,303,458	2,585,692	2,849,551
	Total Exports	67,966	65,330	65,108	69,208	90,552	110,651	107,914	95,621	77,579	96,726	83,417
	Clinker Exports	23,342	25,011	26,223	28,149	35,854	43,096	50,075	41,520	31,587	35,126	34,108
	Total Imports	41,625	39,204	41,622	46,386	57,102	59,568	53,731	50,755	44,358	58,027	49,037
	Apparent Consumption	1,089,448	1,187,770	1,341,399	1,467,416	1,577,757	1,775,603	1,940,789	2,013,478	2,292,917	2,586,237	2,795,750
CIS	Cement Production	44,049	55,582	62,346	71,930	76,998	88,434	97,097	91,121	75,834	83,585	92,196

	Total Exports	3,686	3,775	5,017	6,011	7,466	7,973	6,456	4,089	4,671	3,568	2,718
	Clinker Exports	707	460	420	696	1,103	674	573	265	1,576	1,981	934
	Total Imports	1,528	1,463	1,869	3,051	4,616	5,559	8,940	13,633	7,798	7,130	7,788
	Apparent Consumption	42,633	53,861	59,662	68,959	75,753	85,998	100,030	100,340	78,632	86,499	97,009
Europe	Cement Production	268,764	271,404	279,755	292,761	304,872	326,973	336,268	319,627	269,741	268,295	274,125
	Total Exports	43,134	41,892	43,986	46,756	48,328	45,790	46,720	53,728	53,085	56,321	48,135
	Clinker Exports	9,064	9,765	9,488	8,733	9,095	8,695	8,796	9,934	10,731	9,990	8,983
	Total Imports	31,439	32,705	34,803	38,192	39,745	44,309	44,305	35,706	26,763	25,266	26,282
	Apparent Consumption	259,551	264,897	272,276	285,207	295,086	319,669	326,206	304,957	254,084	251,488	258,195
Oceania	Cement Production	7,809	8,871	9,291	10,003	10,405	10,530	10,667	10,880	10,648	9,658	10,058
	Total Exports	531	319	243	151	97	81	149	129	170	186	183
	Clinker Exports	287	79	67	24	35	1	1	41	91	3	2
	Total Imports	557	1,534	1,780	2,722	2,098	2,124	2,470	3,310	2,483	3,119	6,862
	Apparent Consumption	8,307	10,263	11,229	12,809	12,607	11,162	12,357	12,906	11,221	11,626	16,741

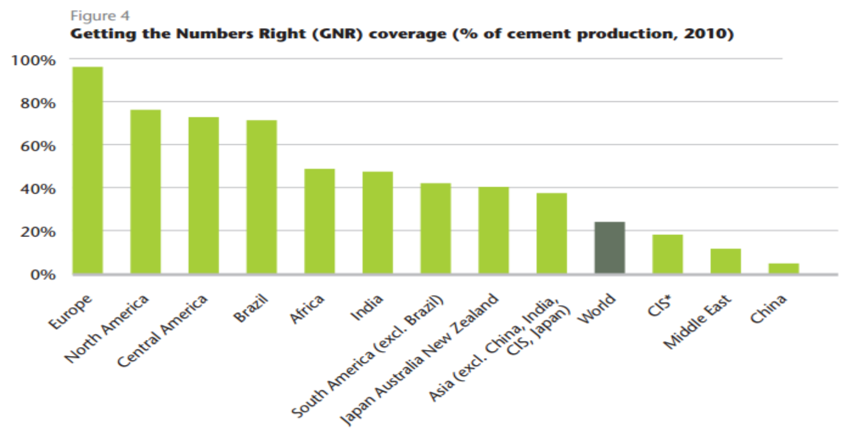

Figure 24 Getting the Numbers Right (GNR) database coverage (WBCSD, 2009)

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