INTERNATIONAL COMPARISON OF ENERGY EFFICIENCY IMPROVEMENT IN THE CEMENT INDUSTRY

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Abstract. Energy savings in the cement industry can be achieved by energy efficiency improvement, and by increased production of blended cements, which reduce the demand for energy intensive clinker. The analysis of selected countries in the OECD, Eastern Europe and Latin America, showed that large differences exist in potentials of energy savings and CO_2 emission reductions. The potential energy savings by energy efficiency improvement vary from 0 to 57% and through production of blended cements vary from 0 to 25%. The total potential reduction of primary energy consumption varies from 4 to 62%, while the potential reduction of (process and energy related) CO_2 emissons varies from 3 to 42%. The differences are caused by the efficiency of the plants, current structure of the industry and the availability of indigenous additives to blend the cements. The differences between countries in the potentials of both measures show that, although total potential savings in countries may be comparable, different strategies should be applied for cost-effective implementation.

INTRODUCTION

Ways must be found to reduce anthropogenic emissions of greenhouse gases because there is a risk that they may lead to climate change. With regard to the most important greenhouse gas, carbon dioxide, an obvious way is reducing the energy consumption by improving the efficiency of energy conversion and consumption processes. A detailed analysis is needed of current energy efficiency and of the options available for improving the energy efficiency of a nations' industry. These analyses must take differences in the industrial structure into account.

The global cement industry is a large energy consuming industrial sector, using annually 1-2% of the world primary energy demand. It is responsible for over 2% of the global anthropogenic CO_2 emissions, due to the use of fossil fuels and generation of non-fuel related emissions (due to the decarbonisation of limestone). Cement production is widely spread over the world (over 80 countries), with an annual production of 1150 Mtonnes (1990).[1] This makes the cement industry an interesting sector to analyze and compare the potentials for energy savings and CO_2 emission reduction in various countries. Cement is produced by burning limestone to make clinker. The clinker is blended with additives to produce different types of cement. The main energy consuming step is the clinker production. Energy savings are possible by energy efficiency improvement and by increasing the use of additives, thereby reducing the clinker demand. The use of blending additives will reduce the CO_2 emissions due to the fuel use in clinker making, and also the decarbonisation in the clinker making process. Fossil fuel use can also be reduced by using selected wastes as fuel.

In this paper we will investigate the potentials for energy savings and emission reduction using both paths. We will do so for a number of OECD, Eastern European and Latin American countries. We will discuss the methodology, followed by a brief description of the production process. Next, we will analyse the potential for energy efficiency improvement, taking the current structure of a nation's cement industry into account, and the potential energy savings due to the increased use of (nationally available) additives in cement making. The results will be compared for the investigated countries and discussed.

METHODOLOGY

The study investigates the specific energy consumption (SEC), that is defined as the amount of energy (in units of enthalpy) needed to execute a certain activity (i.e. the production of a tonne of cement). In this study the SEC_p of a process is equal to the primary energy demand, described by the fuel consumption of the process (SEC_f), and the electricity consumption (SEC_e) divided by the electricity generation efficiency to estimate primary energy demand for electricity production. In this study the public electricity generation efficiency is assumed to be 38% for all countries.† We do not account for efficiency differences caused by combined heat and power (CHP), as this currently plays a limited role in cement making.

The SEC is influenced by three main factors: type of products made, type of raw materials used, and the efficiency of the processes used. The former two are called structural factors. Although the type of primary energy carrier used may also affect the energy efficiency, we will not consider the variety of fuels used. This will introduce a small uncertainty in the results, depending on the type of alternative fuels used (i.e. moisture content).

For our analysis it is necessary to assess the major raw material inputs and cement type outputs that influence the SEC. An important input factor is the distribution of consumption over primary and secondary resources. In the output the main differences can be found in the product quality, i.e. different cement types.

Within an industrial sector several processes can be used to produce a material, each with its own SEC. Therefore, the composite SEC of a sector is a function of the distribution over the different processes utilised within the sector. This is described by formula 1.

$$SEC = \sum_{p=1}^{p=n} SEC_p \cdot \frac{V_p}{V} \qquad (GJ/tonne) \qquad (1)$$

where:

SEC: composite SEC of an industrial sector in a country with n processes, expressed in GJ/tonne

SEC_p: SEC for process p (process with a well described input (feedstock) and output (product), expressed in GJ/tonne

V_p: production volume of product p, expressed in tonne

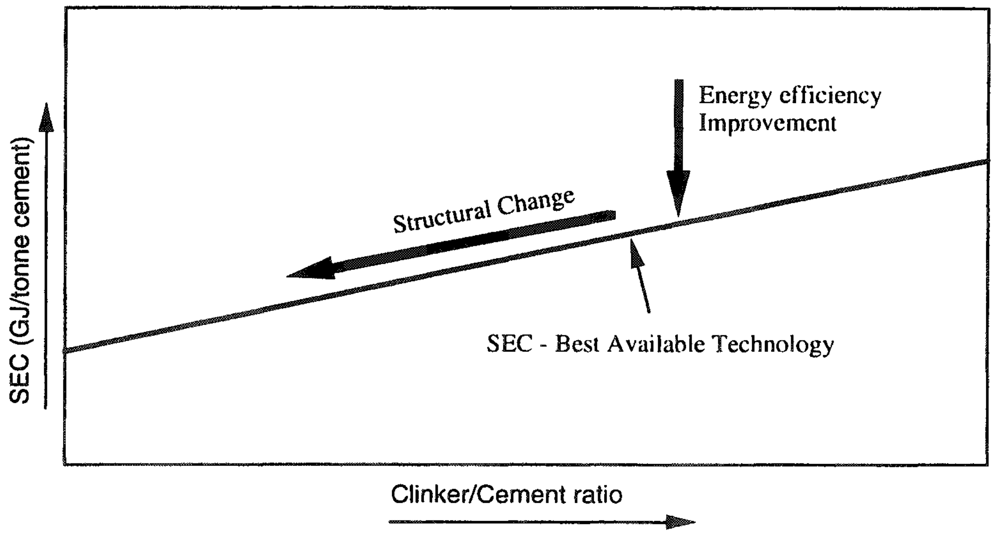
V : total sum of production volumes of n products p, expressed in tonne

Using formula 1 it is possible to compare the SEC of a sector in several countries, when data on a disaggregated level are not available. The SEC is then presented as a function of the main structural factor (see Figure 1). The potential for energy efficiency improvement can be estimated by calculation of the difference in energy consumption if SEC_p is replaced by the SEC of the best available technology; $SEC_{p,BAT}$, where best available technology is defined as the lowest SEC technically feasible within a set period, i.e. the year 2000. This is presented schematically in figure 1, as a movement parallel to the y-axis.

The energy savings due to structural change can be estimated by calculating the possible structural change towards a lower composite SEC, taking geographic factors into account. For cement making this means the increased production of blended cements, presented in figure 1 as moving along the horizontal axis, while the SEC is following the diagonal (representing the SEC_{BAT}). In this analysis we assume that the structural change is limited by the availability of local resources, excluding imports, while maintaining the product output (V) at the level of the reference year. The total energy savings potential is determined by the sum of the potentials of energy efficiency improvement and structural change, accounting for mutual interference.

† In this way the differences in energy efficiency can be assigned totally to the cement industry, and are not caused by differences in electricity generation efficiency in the individual countries. In reality the total primary energy savings will depend on the generation efficiency.

Figure 1. A schematic presentation of the potentials for energy saving in cement production. On the vertical axis the SEC (expressed as GJ/tonne cement) is depicted, as function of the clinker/cement production ratio on the horizontal axis. Energy efficiency improvement is represented as a downward movement along the vertical axis. A movement parallel to the diagonal SEC_{BAT}-line represents a change in the clinker/cement-ratio.



CEMENT PRODUCTION

Cement production involves two main steps. Clinker production is the first and most energy-intensive step. Clinker is produced by burning a mixture of materials, being mainly limestone ($CaCO_3$), silicon oxides (SiO_2), aluminium and iron (III) oxides. Clinker can be produced by two process types: the wet and dry type, referring to the raw materials grinding process. Several configurations including mix-forms like semi-wet and semi-dry exist for both types. The dry-type is the modern and more energy efficient configuration. The wet-process is used because the grinding of the raw materials is easier, or if the raw materials contain more than 20% moisture. The ground raw materials are fed to a rotary kiln, in which they are burned. First the water is evaporated, after which the chemical composition changes, and a melt is produced. The melt is cooled rapidly. In modern kilns the raw material is preheated (in 4-5 stages), using the waste heat of the kiln, and/or pre-calcined. Besides rotary kilns, also (often less energy efficient) small scale shaft kilns are used. The concentration of several components in the limestone affect the SEC slightly. The raw materials for the production of Portland-cement are blended until the mixture contains 76-78% calcium carbonate.[2] The fuel mix for cement production differs from country to country. However, we were not able to obtain reliable statistical data concerning the nature of the alternative fuels used and on the volumes consumed. Therefore, this has not been taken into account for the calculation of the CO_2 emissions. The cooled clinker is ground in ball mills and/or roller presses and blended by (simultaneous) grinding (and mixing) with additives (e.g. gypsum, anhydrite, pozzolana, fly-ash, blast furnace slags) to produce the cement. Drying of the additives may be needed in this stage. Increasing the realtive proportion of blending additives will reduce the clinker demand, thereby reducing the energy intensity of the produced cement.

The SEC_{BAT} for clinker production is assumed to be 3.05 GJ fuel/tonne clinker for a dry process short kiln with a 4-stage preheater.[3,4] Although fuel consumptions of 2.90-2.92 GJ/tonne clinker have been reached in plants in the US (Seattle)[4] and Taiwan (Hualien),[3] it's not certain if these values are representative for all countries due to differences in moisture content of the raw materials. The value of 3.05 GJ/tonne clinker is the guaranteed value for the above mentioned plants, and comparable energy consumptions have been nearly reached in rebuilt Central-European plants.[5] Electricity demand of ground clinker is assumed to be 0.36 GJ_e/tonne (derived from Ref.7). The figures are corrected for the amount of energy used to blend the cement. The energy consumption for drying is estimated at 0.75 GJ-fuel/tonne blast furnace slag[7] and none for fly-ash,[7] and electricity consumption for grinding and blending at 0.24 GJ_e/tonne additive.[8]

Quality of blended cements is comparable to portland cement, the main differences being lower early strength but higher final strength, and improved resistance to sulphates and seawater.[9] Internationally a wide variety of standards for cement compositions exist. Worldwide 876 cement standards exist, and in Western-Europe alone 50 different national standards exist for blended cements. In 1991 only in 59 countries blended cements are standardized.[10] Western-European countries show the highest application rate of blended cement types. Sales figures show the lowest use of Portland cement in Austria (7% of sales), while other countries still use over 90% portland cement.[11] For the analysis of the potential for structural change we will assume 3 types of cements, presented in table 1.

Table 1. Assumed compositions of cement types. Derived from European standard ENV 197-1 (1992). For a comparison to ASTM standards the reader is referred to Dutron.[12]

Cement Type	Clinker (%)	Filler[1] (%)	BF-slag (%)	Fly-ash (%)	Pozzolanes (%)
Type I Portland	95%	5%	-	-	-
Type II Portland composite	65%	5%		← 30%	→
Type III Slag cement	30%	5%	65%	-	-

Note:
1. Mainly gypsum and anhydrite are used as filler.

SELECTED COUNTRIES AND CEMENT PRODUCTION

In this study we assess the potentials for energy savings in a number of OECD countries, economies in transition in Eastern Europe and developing countries in Latin-America. Globally the 1990 production of cement is subdivided as follows: 34% (390 Mtonnes) in OECD countries, 5% (55 Mtonnes) in Africa, 38% (433 Mtonnes) in Asia (excluding Japan), 7% (84 Mtonnes) in Latin-America and 16% (188 Mtonnes) in the economies in transition.[18] China is the world's largest cement producer with 210 Mtonnes in 1990, and still growing at a high rate.[18] The cement production and sector characteristics of the investigated countries are presented in table 2. Together the analyzed countries produce 35% of the world cement demand, and emit nearly 30% (see table 2) of the estimated CO_2 emissions by the global cement industry.[13]

Table 2. Characteristics of the cement production in the selected countries. The specific energy consumption figures are expressed in GJ/tonne cement.

Country	Production (ktonnes)	Clinker/Cement ratio (%) [1]	SEC-Fuel (GJ/tonne)	SEC-Electr. (GJ_e/tonne)	SEC-Primary[2] (GJ/tonne)	CO_2 Emissions[3] (Mtonnes C)
OECD [4]						
Belgium (B)	6766	71%	3.19	0.37	4.2	1.2
Denmark (DK)	1597	95%	4.50	0.55	5.9	0.4
France (F)	26827	78%	3.25	0.39	4.3	5.1
Germany (D)	27700	83%	2.75	0.40	3.8	5.5
Ireland (IR)	1869	95%	3.75	0.42	4.9	0.4
Luxembourg (L)	582	50%	1.79	0.30	2.6	0.1
Netherlands (NL)	3479	27%	1.48	0.22	2.1	0.3
Portugal (P)	6743	90%	2.98	0.38	4.0	1.4
Spain (E)	28217	81%	3.01	0.38	4.0	5.6
United Kingdom (UK)	15764	97%	4.03	0.44	5.2	4.0
USA (US) [5]	67714	94%	4.33	0.52	5.7	17.6
Eastern Europe						
Bulgaria (Bul) [6]	4900	87%	5.7	0.4	6.7	1.4
Hungary (Hun) [6,10]	3900	82%	4.2	0.4	5.3	0.8
Poland (Pol) [7]	12482	82%	5.0	0.4	6.1	3.3
Slovak Rep. (SR) [8]	3780	74%	3.4	0.5	4.7	0.8
former USSR (FSU) [6,10]	137300	72%	6.3	0.4	7.3	34.9
Latin America [9]						
Argentina (Ar)	3580	90%	3.86	0.46	5.1	0.8
Brazil (Br)	26030	79%	3.29	0.45	4.5	5.0
Colombia (Co)	6180	82%	4.80	0.44	6.0	1.5
Costa Rica (CRi)	750	93%	3.33	0.48	4.6	0.2
El Salvador (Sa)	632	95%	3.88	0.42	5.0	0.1
Guatemala (Gu)	920	90%	3.20	0.40	4.3	0.2
Honduras (Ho)	580	85%	3.65	0.47	4.9	0.1
Uruguay (Ur)	430	90%	5.02	0.43	6.2	0.1

Notes:

1. The ratio between clinker and cement production in the reference year is given; 2. The primary energy consumption is calculated assuming an electricity generation efficiency of 38%; 3. The CO_2 emissions are calculated assuming an emission of 136 kg C/tonne clinker[13], an average of 24.8 kg C/GJ fuel (derived from Ref.11 and 14) and the countries specific C-emission for electricity generation as given by Ref.15; 4. Reference year 1989, except Germany reference year 1990. Source: Ref.16; 5. Reference year 1988. Sources: Ref.14 and 17.; 6. Reference year 1990. Source: Ref.18.; 7. Reference year 1990. Source: Ref.19; 8. Reference year 1990. Source: Ref.20; 9. Reference year 1988. Source: Ref.21; 10. The specific electricity consumption has been estimated to be equal to the SEC in Poland.

ENERGY EFFICIENCY IMPROVEMENT

The potentials for energy efficiency improvement have been calculated assuming the application of best available technology, without changing the structure of the sector. Figure 2 and 3 present the results for the OECD and the other countries respectively. The potential for energy efficiency improvement is expressed as the distance between the upper point and the position on the line, representing the SEC_{BAT} at various sector structures.

Figure 2. Energy efficiency of cement production in 11 OECD countries. The specific primary energy consumption (GJ/tonne cement) is depicted as a function of the clinker/cement production-ratio in the reference year. The upper points (□) depict the SEC in the reference year, while the lower points (■) on the line represent the SEC_{BAT}.

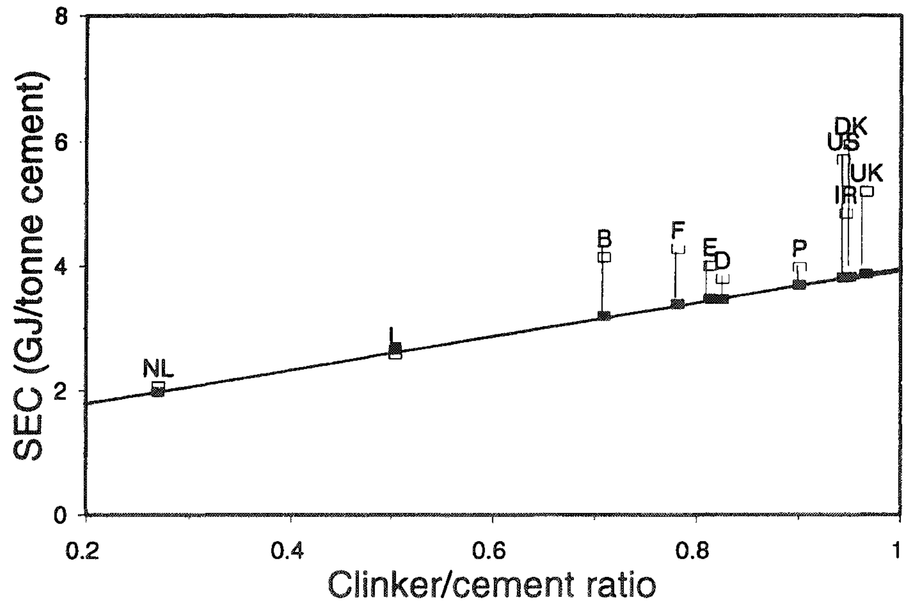
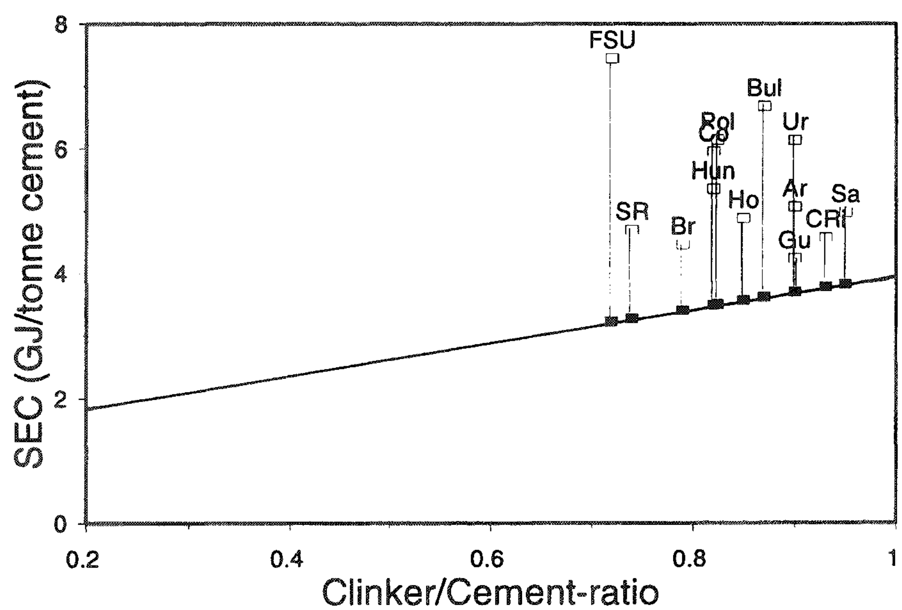


Figure 3. Energy efficiency of cement production in some Eastern European and Latin American countries. The specific primary energy consumption (GJ/tonne cement) is depicted as a function of the clinker/cement production-ratio in the reference year The upper points (□) depict the SEC in the reference year, while the lower points (■) on the line represent the SEC_{BAT}.



The potential savings on primary energy vary from 0% to 57% relative to 'best available technologies'. The high potential savings in various countries are mainly due to the high share the wet process still has in the clinker production (e.g. Poland, USA and former-USSR). The uncertainties in the SEC_{BAT} are estimated at 10%, due to the differences in the moisture content of the raw materials and additives. It is not possible to estimate the total error in the results, because the statistical errors are unknown. The high figures in the Eastern-European countries should be interpreted with care, because the transition process in the economies has reduced capacity utilization dramatically, which can be expected to further increase the specific energy consumption of the clinker kiln.
The high figures in some countries with a relatively small cement production should be interpreted carefully, as possible statistical errors have a larger influence on the SEC. The small scale of the plants will also influence the SEC_{BAT}, as the SEC_{BAT} is for a modern large scale plant.

STRUCTURAL CHANGE AND ENERGY SAVINGS

The energy savings and emission reduction potentially obtainable by increased use of blended cements is dependent on the available additives. In this analysis we assume that the availability is determined by the indigenously available resources commonly used to blend cements; blast furnace slags, fly-ash and natural pozzolanes (volcanic material). Less common materials have not been assessed, e.g. silica fume, non-ferrous slags and burnt shale. That we assume that there is no international trade in additives is a reflection of the fact that international trade of additives is currently limited. The US imports small volumes of granulated slags for cement making.[22]
Blast furnace slags are formed in pig iron production. Pig iron is produced in 47 countries worldwide, with a total estimated production of 532 Mtonnes in 1990.[23] The amount of slag is determined by the purity of the iron ores, coke and used process additives. In cement making only granulated slags can be used. In principal, every blast furnace can produce granulated slags by quenching, although in some countries slags are air-cooled (e.g the US). Air-cooled slags can not be used in cement making. Minimal investments are necessary to change production to granulated slags. We will assume that all slags are available for cement making. The calculation of available slags is based on the pig iron production[23] in 1990 and an assumed slag production of 200 kg/tonne pig iron for 'best practice' blast furnaces (derived from Ref.23). The actual slag production is estimated on basis of the iron ore consumption relative to the pig iron production,[23] and multiplying this factor with the 'best practice' slag production.[†]
Fly-ashes are produced by the burning of coal in electric power generation, and production depends on the ash content of the coals used. In this study we assume that the coal has an average ash content of 10%, based on the situation in the USA.[24] We also assume that the fly-ash is 80% of total ash produced. Coal use in power plants is based on IEA statistics,[25] and converted to tonnage using the country specific conversion factors, as determined by IEA in 1990 for bituminous coal.[25] We assume that 50% of the fly-ash has characteristics suitable for cement blending.
A number of volcanic materials are natural pozzolanes, and can therefore replace clinker in cement. The available data on production volumes is limited to a small number of countries,[26] while reserves are available in many countries. For these countries we assume that 50% of the mined volume in 1989 can be applied in cement making. The imported value in the US of these materials was 9 -13 US$/tonne in 1989,[26] comparable to the price of imported granulated slags; 10 US$/tonne.[22]
The minimum share of Portland cement in the total production volume has been set at 25%, or equal to the current production share in a country, whichever is lower. The limit assumes that cements are needed with a high early strength, and this share is based on minimum market shares in a number of countries,[11] although a few countries have smaller market shares for Portland cement.[11,27]
In the calculation of the energy savings the energy consumption (0.2 GJ/tonne additive) for transport of the additives over a distance of 100 km has been taken into account (using a mix of road traffic and inland shipping). The savings are calculated on basis of the observed SEC's in the reference year (see tbale 2). The results are presented in table 3.

[†] This represents a lower boundary of the available amount of slags, as coke and coal consumption of the blast furnace and process additives will also influence the produced volume of slags.

Table 3.Cumulative results of energy efficiency improvement and structural change in the selected countries.

Country	Effects Structural Change			Energy Eff.	Cumulative Effects Efficiency Improvement and Structural Change				
	Current C/C ratio (%)	Possible C/C ratio (%)	Savings Primary Energy (%)	Savings Primary Energy (%)	Cumulative Savings prim. energy (%)	Resulting SEC-Fuel (GJ/tonne)	Resulting SEC-Electr. (GJ_e/tonne)	Resulting SEC-Primary Energy (GJ/tonne)	CO_2 Emissions (Mt C)
OECD									
Belgium	71%	64%	7%	23%	28%	2.15	0.32	3.0	1.0
Denmark	95%	73%	10%	36%	42%	2.21	0.33	3.1	0.3
France	78%	77%	2%	21%	22%	2.44	0.33	3.3	4.5
Germany	83%	60%	19%	9%	26%	2.00	0.31	2.8	4.0
Ireland	95%	91%	3%	21%	24%	2.77	0.35	3.7	0.4
Luxembourg	50%	45%	5%	0%	5%	1.69	0.29	2.5	0.1
Netherlands	27%	27%	0%	4%	4%	1.06	0.27	1.8	0.3
Portugal	90%	90%	0%	7%	8%	2.75	0.35	3.7	1.4
Spain	81%	81%	2%	13%	15%	2.50	0.34	3.4	5.2
United Kingdom	97%	63%	25%	25%	44%	2.06	0.32	2.9	2.4
USA	94%	64%	24%	33%	49%	2.07	0.32	2.9	10.3
Eastern Europe									
Bulgaria	87%	82%	5%	46%	49%	2.5	0.3	3.4	0.9
Hungary	82%	76%	6%	35%	39%	2.4	0.3	3.3	0.7
Poland	82%	66%	16%	43%	52%	2.1	0.3	2.9	2.1
Slovak Rep.	74%	72%	3%	30%	32%	2.3	0.3	3.2	0.7
former-USSR	72%	62%	12%	57%	62%	2.0	0.3	2.9	20.6
Latin America									
Argentina	90%	80%	7%	27%	32%	2.55	0.34	3.4	0.6
Brazil	79%	77%	1%	24%	25%	2.49	0.33	3.4	4.4
Colombia	82%	82%	0%	41%	43%	2.54	0.34	3.4	1.1
Costa Rica	93%	93%	0%	18%	18%	2.84	0.35	3.8	0.2
El Salvador	95%	95%	0%	23%	23%	2.90	0.35	3.8	0.1
Guatemala	90%	90%	0%	13%	14%	2.75	0.35	3.7	0.2
Honduras	85%	85%	0%	27%	29%	2.59	0.34	3.5	0.1
Uruguay	90%	90%	0%	40%	40%	2.75	0.35	3.7	0.1

From table 3 it can be seen that the potential energy savings through structural change differ from 0% to 24% among the selected countries. The availability of additives is especially low for a number of the Latin American countries due to the lack of indigenous pig iron production and the use of non-coal based power sources (e.g. hydropower). The potential application of fly-ash is very limited in France due to the high penetration of nuclear energy. Coal using countries like Denmark and Ireland lack an iron industry, but still can use fly-ash. In countries with a heavy industrial base and coal based power production (e.g. Germany, the former-USSR, United Kingdom and the USA) large potentials for energy savings and CO_2 emission reduction in cement making exist.
The effects of the expanded use of natural pozzolanes could not fully be evaluated, due to the lack of data. Natural pozzolanes are geologically available in a large number of countries. Also we did not analyze the effects of using alternative pozzolanic materials (see discussion).

COMPOSITE RESULTS

Table 3 presents the potential composite savings and emission reduction due to energy efficiency improvement and structural change for the selected countries. Although generally the potential energy savings due to structural change are smaller than the potential of energy efficiency improvement, the relative influence on the CO_2 emission is larger than on energy consumption, due to the reduced amount of limestone that is decarbonized.

IMPLEMENTATION OF ENERGY SAVINGS AND BLENDED CEMENTS

A wide body of literature has also identified potentials for energy efficiency improvement in the cement industry, and blending cements has also previously been considered (a.o. Ref.9, 27,28,29). The potentials have been calculated using a $SEC_{p,BAT}$, giving an upper bound on the potential savings with currently best available technology. Upgrading of existing plants might limit the potential savings due to cost constraints. Detailed analyses can estimate the costs of upgrading. The introduction of energy efficient technologies and blended cements is determined by a large number of factors. We will discuss these issues briefly. Further research in these fields is ongoing.
Although current low coal prices (the main fuel in cement making) decrease interest in energy efficiency improvement, energy costs still represent approximately 20-30% of the production costs of cement making. Generally in industry the main barriers in adopting energy efficient technologies are the effects on product quality, expected reliability of the new technology, and budgetary limits.[30,31] These barriers seem to be valid for OECD countries (The Netherlands, Germany), and for some economies in transition (Czech and Slovak Republics). Farla and Blok[32] studied the barriers to adoption of energy efficient measures in the cement industry in the Netherlands. They found that the main energy savings in the past have been obtained by replacement *not* for energy efficiency goals. Observed barriers were the long lifetime of the equipment, fear for decreased product quality and doubts about the technical feasibility of a measure.[32]
Empirical research on implementation barriers in developing countries is very limited, but the barriers found in economies in transition and OECD countries might apply for these countries as well, besides various organisational barriers (see for instance Ref.33 and 34).

As stated 58 countries adopted standards for blended cement types, which means that over 25 cement producing countries allow the use of Portland cement only. The introduction of standards for blended cements in Western-Europe has increased the production and use of these cements. Currently, countries such as Austria and Luxembourg show Portland cement market shares of less than 10%. Standardisation of blended cements and of the additives[28] would be a first step to increase the market shares. Of the selected countries Colombia, Costa Rica, El Salvador, Guatemala, Honduras, Ireland and Uruguay have no standards for blended cements.[27] When adopted, experience in a number of European countries and India showed fast implementation of blended cements.[27] However, the situation in some countries (e.g. Canada, UK, USA) suggests that there are also other barriers. Possible barriers are that the quality of blended cements is still unknown by cement users or that blended cements are not used due to a traditional approach in the building industry. Building codes might limit the use of blended cements[†], or the produced form of the additives is not suitable (e.g. air cooled slags in the USA).

[†] Testing the strength of a structure after a short period only will limit the use of blended cements because the strengthening process is slower. However the strength after 28 days is comparable, and the ultimate strength is after 360 days even higher.[9]

Although the potential for structural change is limited in a number of countries, it is still worthwhile to increase blending because the increased use of blended cements will make it possible to close the inefficient (wet-process) clinker kilns at low costs. This will lead to higher savings on energy and CO_2 emissions as shown in table 3, where the average $SEC_{clinker}$ was used.
This suggests that the costs of implementing CO_2 emission reduction strategies will depend on the strategy itself, as on the needed investments.

DISCUSSION

For the analysis of the feasible production volume of blended cements assumptions have been made on the availability of additives, e.g. slag production and ash content. The assumptions could be refined by actual data, which are, however, not available in international statistics. Comparison of the potential for cement blending with Bucchi[27] shows differences, which can not be explained by the differences in reference years. Unfortunately, Bucchi[27] does not present the assumptions used. The fly-ash volumes have been calculated assuming hard coal with 10% ashes. However, a number of countries use lignite, brown coal or sub-bituminous coals as well (with a lower ash content and lower heating value). Because fly ash charactersitics vary widely, not all available fly-ash is suitable† for cement making.[27] International statistical data on fly ash quality is not available. The current application of fly-ash might also be limited by low fly-ash removal and recovery rates, especially outside OECD countries.
Statistics on the availability of natural pozzolanes and alternative pozzolanic materials, e.g. silica fume, are rare or non-existent. However, volcanic pozzolanes can be found in a large number of countries. Further research on natural pozzolanes might increase the potential production of blended cements.‡ This is especially interesting for the Latin American countries. Further analysis of the properties of cements using alternative blending materials, see Sprung,[35] could increase the production of blended cements.
The availability is also determined by the indigenous production of the additives. International trade of additives might increase the availability, although only eight of the selected countries have excess ashes and slags after maximum penetration. We assumed a 25% market share of Portland cement. International trade of cement might increase the savings in a country, as it will reduce the minimum Portland production, based on the availability of additives. However, on the international level the effect will be limited, due to the assumed market share. Reduction of the assumed market share to levels found in Austria and Luxembourg (<10%) will increase the overall savings for those countries with excess additives. The market share will depend on the application of the cement in relation to cement characteristics. Further research is suggested to determine the maximum market penetration of blended cements. International trade of additives and cement will increase transport distances and hence reduce energy savings. This is also true for large countries, e.g. Brazil, USA and former-USSR. A geographical analysis of resources location and cement plants will reduce the uncertainty of the results.
The reliability of the calculated energy savings depends on the energy needed to dry the slags, which depends on the moisture content and the energy needed for grinding. The uncertainty is estimated at 10% of the energy savings. The uncertainties due to the availability of additives might be larger.

The SEC_{BAT} was determined for a large capacity clinker plant. In theory also small plants are able to reach this value, but cost constraints might limit the maximum efficiency. Therefore, the potentials for energy efficiency improvement in countries with small clinker production capacity, e.g. some developing countries, might be smaller.
Further reduction of the CO_2 emissions is possible by using fossil fuels with a lower carbon intensity (e.g. natural gas), non-fossil fuels like biomass, or burn wastes (municipal solid wastes, tires, chemical wastes). Substitution of

† A sensitivity analysis has been performed, assuming that theoretically 100% of the fly-ash would be suitable for cement making. The analysis showed that the possible clinker/cement ratio would decrease, increasing the primary energy savings due to structural change for Belgium to 10%, Ireland to 6%, Bulgaria to 9% and Hungary to 10%. Compare the new savings potentials to table 3. The total effect on the overall results is limited.

‡ We analyzed the effect of the availability of alternative additives for all countries, assuming availability equeal to 20% of the cement produced. This is comparable to the introduction of Type-II cements blended with 6-35% limestone. Limestone is available in all clinker producing countries. This showed an increase of the potential savings due to structural change, reducing the market share of Portland cement to 25% for all countries. The Clinker/Cement-ratio would vary between 27 and 78%, and the primary energy savings between 0 and 25% due to structural change. The total energy savings would increase.

fossil fuels by direct use of waste up to 20%[36] and of flax up to 20-30%[37] has been proven successfully. In Austria and Italy, gas produced by gasification of biomass and municipal solid waste respectively is used successfully in cement kilns.
The cost-effectiveness of the reduction of energy use and CO_2 emissions depends strongly on the implementation strategy. Introduction of blended cements can lead to closure of old inefficient clinker plants, at low costs. This will reduce the need of upgrading old clinker plants. On the other hand replacement of inefficient plants by new plants could be more cost-effective than upgrading of relatively new plants. The optimal strategy will depend on national conditions, e.g. structure of cement industry and market and the potentials of energy efficiency improvement and structural change respectively. This means that for each country a different optimal implementation strategy should be developed. Practices of cement use showed that large differences exist in the application of blended cements, even when standards exist for blended cements. Further research of barriers, other than blended cement standards, is needed to optimize the implementation strategy.

CONCLUSIONS

Although the energy benefits of energy efficiency improvement and blending cements (using blast furnace slags and fly-ash) have been shown in the past, no comparative analysis of national potentials has been executed yet. The current analysis showed that large differences exist in potentials of energy savings and CO_2 emission reductions for the analysed countries, both for energy efficiency improvement (0-57%) and production of blended cements (0-24%). The cumulative potential energy savings are on the order of 4-62% for the selected countries. The potential reductions in CO_2 emission of the cement industry are estimated at 3-42%. The differences are caused by the current efficiency of the plants and structure of the industry and the availability of additives to blend the cements. The differences in the potentials for both measures show that, although total savings may be comparable, different strategies should be applied for cost-effective implementation.

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