Cement Production

HIGHLIGHTS

- **PROCESSES AND TECHNOLOGY STATUS –** The manufacture of cement is a two-phase process. Clinker is first produced in a kiln system from calcareous (limestone, chalk or marl) and argillaceous (clay or shale) materials, with addition, in some cases, of small amounts of corrective materials (sand, waste bauxite, iron ore). Various fossil fuels and waste fuels are used in this process to reach the reaction temperature of 1450 °C. Secondly, the clinker is ground with calcium sulphates and with industrial processes wastes such as blast furnace slag, limestone, natural pozzolana and industrial pozzolanic materials, e.g. fly ash, silica fume and burnt shale. 90-150 kWh/t cement are used in the process. Two basic types of clinker production processes exist, depending on the way the row materials are prepared before entering the kiln system: in the wet method, water is added to form a wet thick slurry whereas the dry process is based on drying the bulk materials to form a dry powdered meal. The choice of process depends on moisture content of the available raw material. When wet raw materials (moisture content over 20%) are available, the wet process can be preferred. However, in Europe, today's new cement plants are all based on the dry process as the wet process requires approximately 56 to 66% more energy. For dry processes, current state-of-the-art technologies are kiln systems with multistage cyclone preheaters and precalciner. Capacities of up to 15,000 tonnes clinker per day are achievable and unit consumption as low as 3.3 GJ/t clinker.
- **COSTS –** Investment costs estimates differ depending on the source. According to the International Energy Agency [IEA, 3] building a new plant with a capacity of 1 million tonnes/annum of cement using the conventional dry processes with 5-stage preheater and precalciner costs €263 per tonne/annum (€ 2010). The investment cost increases to some €558/t if CO_2 emissions produced in the process are captured (and stored) using post-combustion technologies and to €327/t using oxy-combustion technologies. According to the European Cement Research Academy [ECRA, 2] new plants with capacities of 2, 1 and 0.5 million tonnes per year, using state-of-the-art technologies the unit investment costs is €130, €170 and €250 per tonne/annum respectively (€ 2007). Operation and maintenance (O&M) costs (including labour, power and fuel costs, but no deprecation) amount to €29/t for new, state-of-the-art plants and to €32/t for a typical existing plant with no CO2 capture. O&M costs are estimated to rise to €66 and €45/t for plants equipped with post-combustion CO2 capture oxy-combustion capture, respectively. O&M costs include fixed operating costs, fuel cost, electricity cost and other variable operating costs).
- **POTENTIAL & BARRIERS –** An important innovation in cement production technology relates to the use of CO_2 capture and storage (CCS) technologies to reduce the CO_2 emissions, with potential reduction of up to 95%. Post-combustion capture and oxy-combustion CO_2 capture are promising technology options, but none has been tested so far in industrial-scale cement plants. Full-scale CCS demonstration projects are expected between 2020 and 2030 and commercial deployment after 2030. It is estimated that between 10% and 43% of the global cement capacity could be equipped with CCS in 2050. Apart from CCS technology, no breakthrough technologies are expected to cause a significant changes of electricity and thermal energy consumption in cement production. Electricity demand could decline from the current average value of 110 kWh/t of cement (2006) to some 105 kWh/t cement in 2030. Thermal energy demand could decline from the current 3.38 GJ/t (2006) to 3.3 GJ/t clinker in 2030. However, if CCS technologies are implemented, specific thermal energy and power consumption could increase considerably. Assuming the CCS implementation in some 20% of the cement production capacity in 2030 and up to 40% in 2050, then power demand for cement plants would increase to 115-130 kWh/t cement in 2030 and to 115-145 kWh/t cement in 2050.

PROCESS OVERVIEW – Cement is a solid material made of clinker, gypsum and other additives. It is mainly used to form concrete, a conglomerate of cement, water, fine sand and coarse aggregates, widely used for civil engineering constructions. Cement has a strong hydraulic binder power. Reacting with water it becomes a hard and durable material in a few days [1, 7, 8]. Global cement production has grown steadily from less than 200 million tonnes in 1950 to more than 2500 million tonnes in 2006. Today's growth is largely driven by rising production in emerging economies and developing countries, especially in Asia. In 2006, almost 70% of the world production was in Asia (47.4% in China, 6.2% in India, 2.7% in Japan, 13.2% in other Asian countries), about 13.4% in Europe and the remainder in Africa (4%), in the US (3.9%), and in other American countries (5.8%). The EU-27 produced about 268 million tonnes of cement in 360 installations, of which 268 produce both clinker and cement, 90 produce only cement and 2 produce only clinker [1]. ■

Cement Production – The manufacture of cement is a two-step process, notably, *clinker production* and *cement grinding*. **In the first step**, the raw materials are fed to the kiln system to produce clinker. Clinker consists of silicates, aluminates and ferrites of calcium obtained from the reduction of calcium, silica, alumina and iron oxides present in the raw materials. Clinker production starts with quarrying the main natural raw materials, typically limestone, chalk or marl (as a source of calcium carbonate) and clay, iron ore, sand or shale (as a source of silica, alumina and iron oxide). The raw materials is crushed, ground and mixed to obtained a homogenous blend, and then stored. Raw materials handling may be accomplished by modern and energy efficient dry processes or by traditional wet processes. The choice depends on the nature of the available raw

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materials, on energy and final production costs. After the material preparation and prior to entering the kiln system for clinker production, the raw materials are often preheated - to enable the chemical reactions to occur quickly and efficiently in the kiln - and calcined (calcinations) to separate calcium oxides from calcium carbonates contained in the raw materials. During the process, significant amounts of carbon dioxide (CO_2) are released. In the kiln system, calcium oxides are sintered at a typical temperature of 1400-1500°C to form clinker, together with oxides of silica, alumina and iron that are present in the feed materials. The clinker production ends with the cooling phase in a cooler. **In the second step**, clinker is ground (in a grinding mill) with calcium sulphates (gypsum or anhydrite) and with possible additions of other minerals (blast furnace slag, natural pozzolanas, fly ash, silica fume or limestone) to obtain cement with desired performance such as setting time and strength development [1, 5,.7, 8, 10, 12]. A process scheme applicable to both dry and wet processes is shown in Figure 1. ■ **Cement classification** – Civil construction materials vary considerably with regional and climate conditions, availability of raw materials, and economic and industrial development level. This leads to significant variations in composition and national standards for cement. A European standard has been elaborated for most common cements, but cements for special applications such as low-heat cements or low-alkali cements are not included in such standards and special regulations exist at national level. The European standard EN 197-1 describes 27 types of cement, which are divided into 5 groups, as shown in Table 1. While clinker is the main component in all types of cements, the kind and the amount of the other constituents determine the type of cement. For example, Portland cement consists of 95% clinker, whereas Portland-slag cement contains less clinker but contains blast furnace slag in the range of 6 to 35%. All cement types also contain up to 5% of calcium sulphates. In 2005, the most common cement types for EU-25 were Portland Composite cement (58,6%) and Portland cement (27,4%), followed by Blast Furnace Slag cement (6,4%), Pozzolanic cement (6,0%) and Composite cement and other (1,6%) [1, 12].

CEMENT PRODUCTION PROCESSES– The two basic methods to produce cement are the **wet and dry manufacturing processes**. The main difference between wet and dry process is the mix preparation method prior to burning clinker in the kiln. In the wet process water is added to the raw materials to form a raw thick slurry whereas the dry process is based on the preparation of a fine powdered raw meal by raw materials grinding and drying [1, 5]. The choice of the process is mainly based on the nature of the available raw materials [1]. When the moisture content in raw materials is more than 20% (and up to 45%), the wet [12] method is preferred to the dry method [4]. In the past, the wet process was mostly preferred because the homogenization of wet raw materials was easier than that of dry powders. The wet process also enables an easier control of the chemical composition of the raw mix. However, the wet process is more energy intensive and

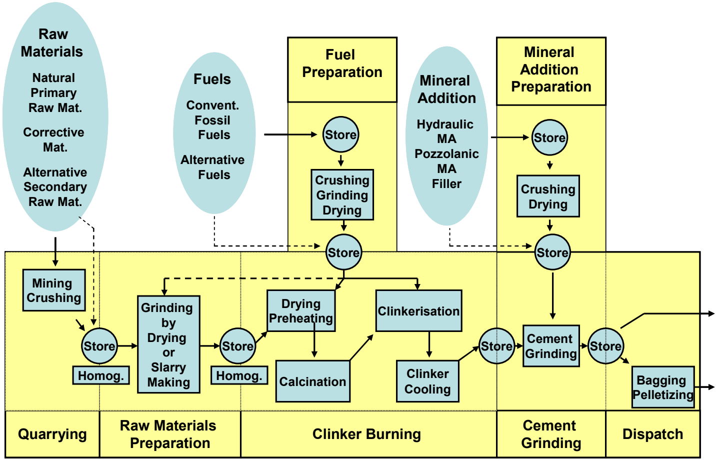

Fig. 1 - Simplified cement production process[5]

Tab. 1 – Cement EU Standard and Composition [5]			
	Types of cement	**Clinker %**	**Other Constituents**
CEM I	Portland	95-100	
CEM II	Portland-slag	65-94	Blast furn. slag
	Portland-silica fume	90-94	Silica fume
	Portland-pozzolana	65-94	Pozzolana
	Portland-fly ash	65-94	Fly ash
	Portland-burnt shale	65-94	Burnt shale
	Portland-limestone	65-94	Limestone
	Portland-composite	65-94	Additives mix
CEM III	Blast furnace	5-64	Additives mix
CEM IV	Pozzolanic	45-89	Additives mix
CEM V	Composite	20-64	Additives mix

expensive than the dry process as it requires the wet slurry to be evaporated before calcination [1, 4, 6, 8]. The total heat requirement with new dry precalciner kiln systems ranges from 850 to 900 kcal/kg which is approximately 56 to 66% of the energy requirement of old wet process kilns (1300-1600 kcal/kg) [9]. For saving energy and reducing costs, if dry raw materials are available as a basic input, traditional wet process plants are usually converted into dry process plants at the occasions of equipment renewal (plant lifetime in the order of 15-20 years). Semi-wet and semi-dry processes are often used as intermediate steps in the conversion to dry processes [1, 5, 6]. As shown in Figure 2, the global

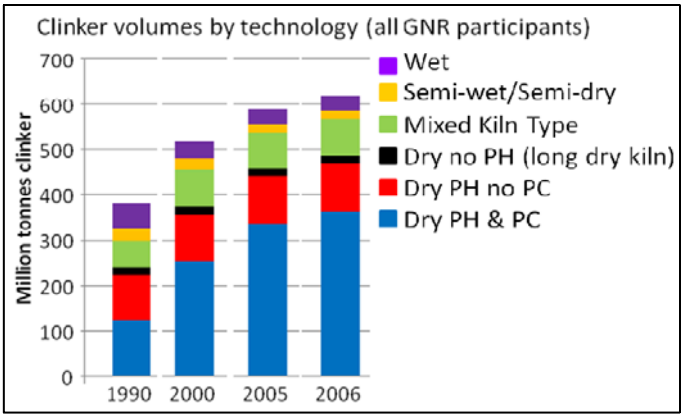

Fig. 2 - Global clinker production per kiln type according to the GNR database [6]

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cement industry is moving towards more energy-efficient dry process technologies. Over the period 1990 to 2006 the share of dry process kilns in total production capacity increased from some 63% to 80%, while the share of wet process technologies decreased from 16% to 5.6%[1]. The quick shift from wet to dry processes is a consequence of the rapid production growth in Asia over the last decade to meet the local demand. To a lesser extent the move is due to the replacement of old equipment in mature countries [6]. In Europe, in 2004 dry process kilns accounted for about 90%, followed by semi-dry/semi-wet technologies (7.5%) and wet process kilns (2.5%). In Europe, new wet cement plants are no longer built. However, it should be noted that cement production is usually based on locally available raw materials because material transportation costs have a significant impact on final production costs [1, 7], and that wet or semi-wet processes are more suitable for raw materials with high moisture content. When wet raw materials are available locally, an assessment may help find out whether a wet process is economically competitive over a dry process based on materials imported from far regions. On the other hand, wet raw materials are not necessarily usable in dry processes as a significant amount of energy may be needed to reduce moisture content and make the materials ready for a dry kiln system.

■ **Materials Flows –** Figure 5 (end of the Brief) shows a more detailed scheme and the material flows for a typical dry process. The dry process requires between 1.5 to 1.6 t of natural raw materials per tonne of clinker [5] - an average consumption of 1.57 t of dry materials per tonne of clinker was reported in the EU in 1997. In addition, an average 0.05 t of calcium sulphate (gypsum or anhydrite) per tonne of cement is needed to control the setting time [1]. The natural raw materials are usually extracted from quarries located close to the cement plants. Natural *primary* materials include calcareous materials such as limestone, chalk or marl (rich in calcium) and argillaceous materials such as clay or shale (rich in silica, alumina and iron). Marl, chalk and clay have an inherently high moisture content. In some cases *corrective* materials such as sand, waste bauxite and iron ore are added in small amounts to ensure that the chemical composition of the raw mix satisfies the process and product requirements [1, 5, 10, 12]. For example, iron ore is needed to improve the quality of the raw mix when the content of alumina in clay is too high and iron content is too low [11]. As the composition of the raw materials may have an impact on the production processes and clinker quality, chemical characteristics of raw materials are carefully analysed and controlled. Only small deviation in the composition of raw materials, including fuel ash, is permitted.

Wastes from industrial production processes are increasingly used as raw materials for cement production. Wastes can be used as partial replacement

[1] Figure 2 is based on the Getting the Numbers Right (GNR) database, which covers 844 cement plants worldwide, of which over 73% cement production facilities in Kyoto Annex-I countries and 20% in Annex II countries. More information about the GNR project and participants is available in [6].

Tab. 2 - Waste used as row material in cement kilns in EU [1]

Raw Materials Group	Examples of used waste as raw materials
Ca group	Industrial lime (waste limestone), Lime slurries, Carbide sludge, Sludge from drinking water treatment
Si group	Spent foundry sand
Fe group	Blastfurnace slag, Pyrite ash, Synthetic hematite, Red mud
Al group	Industrial sludge
Si-Al-Ca group	Fly ash, Slags, Crusher fines
S group	Industry by-product gypsum
F group	CaF_2, Filter sludge

for natural raw materials in clinker or as partial replacement for clinker in "blended" cements (CEM II-V in the European Standard). Typically, the waste is fed to the material preparation system of the cement plant in the same way as the traditional raw materials. Table 2 lists some examples of different types of waste used in cement kilns in the EU-25. Some of these, such as fly ash, are both used as raw materials for clinker production and as ground with clinker to produce cement [1, 13]. To produce blended cements, industry currently uses large quantities of limestone, fly ash (by-products of coal burning in the electrical power creation), blast furnace slag (by-product of iron and steel production), natural pozzolanas (siliceous and aluminous materials that contain more or less reactive silica and various alumino-silicates), silica fume (by-product of silicon and ferro-silicon alloys manufacturing) and burnt oil shale (extracted in the Swabian Mountains and containing mainly lime and clay minerals) [8, 12].

The **water consumption** in state of art cement plants process is around 70 l per tonne of cement [1]. Environmental targets include reducing emissions of dust, carbon dioxide and acid gases, lowering energy consumption and quarrying of natural resources [14]. In 2004, some 14 million tons of traditional raw materials were saved in Europe, corresponding to about 6.5% of the natural raw materials need [1].

■ **Energy Use -** A wide range of solid, liquid and gaseous fossil fuels is used to provide energy for raw materials drying and preheating, and for chemical reactions that sinter the raw materials into clinker in the kiln. An overview of total fuel consumption in the EU-25 according to different types of fuel is shown in Figure 3.

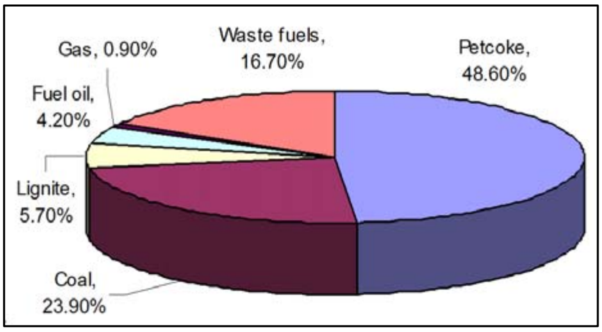

Fig. 3 - Fuel consumption in the EU-25 in 2004 [1]

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The most used solid fossil fuels were petcoke (48.6%) and coal (23.9%). Oil and natural gas are used to a lesser extent as they are in general more expensive, apart from special local resources [1]. The majority of fuel input (65-85%) comes from pulverised solid fuels prepared through hoppers, conveyors and feeders. The remaining part (15-35%) may consist of more difficult combustible fuels that are fed to the kiln in a coarsely crushed or lump form. An important target is to keep the heat losses to a minimum level. Moreover, in order to achieve unchanged clinker structure and cement hydraulic characteristics, the ash content needs to be monitored by chemical analyses of the raw mix composition as fuel ash is absorbed completely into the

materials [1]. Primary fossil fuels are often replaced by waste derived fuels, such as: wood, paper, cardboard; textiles; plastics; RDF; rubber / tyres; industrial sludge; municipal sewage sludge; animal meal, fats; coal, carbon waste; agricultural waste; solid waste (impregnated sawdust); solvents and related waste; oil and oily waste. In Europe, the substitution rate is increasing from some 3% in 1999 to 17% in 2007 [1], but much higher levels are technically feasible. In some European countries, levels of more than 50% have been reached, and individual cement plants have already achieved levels of 80% [2]. The main requirements for waste fuels include net calorific value, low emissions, and other characteristics to favour kiln operation and clinker quality. The use of waste as a fuel may require pretreatment [1, 14].

The **electricity use** in cement production varies between 90 and 150 kWh per tonne [1]. According to the GNR database, in the year 2006, the global average electricity consumption was 111 kWh per tonne of cement. The electricity consumption of 90% of the 844 cement plants covered in the database [2] are between 89 and 130 kWh/t. Significant variations exist between countries and regions [2, 4]. According to the IEA (IEA, 2007), electricity consumptions ranges from 90 to 120 kWh/t of cement, except for the United States, Mexico and Canada where typical figures are all above 120 kWh/t of cement [4]. Grinding may account for a significant part of electricity consumption (up to 100 kWh/t) [4]. In a dry process, the electricity consumption share is 38% for cement grinding, 24% for raw material grinding, 22% for clinker production including grinding of solid fuels, 6% for raw material homogenisation, 5% for raw material extraction and blending, and 5% for conveying, packing and loading [2].

■ **Clinker Kiln Systems** –The main types of rotary kilns for clinker are discussed here: **a)** kiln without pre-heater; **b)** kiln with pre-heater (PH) ; **c)** kiln with both PH and pre calciner (PC). Kilns with PH are preferred to kilns without PH as they have a lower energy consumption. For this reason, long rotary kilns without PH (long dry kilns) are being replaced over time. Thermal energy requirement is further reduced if a PH kiln is also equipped with a PC. New facilities usually include both PH and PC. A preheater (PH) is a series of vertical cyclones in which the material is passed in counter-flow with exhaust gases counter-flow with exhaust gases from rotary kiln so that heat is transferred from the hot gas to the raw meal, which is therefore preheated and even partially calcinated (30%) before entering the rotary kiln. In the 1970s, a 4-stage cyclone preheater kiln (so-called **suspension preheater, SP**) was considered the technology of choice for dry and semi-wet processes. However, a number of different SP kilns is available. Most common SP kilns have between 4 and 6 cyclone stages. The number of stages is determined by the moisture content of the raw materials. Where moisture is less than 8.5%, a PH kiln with 4 to 6 stages may be used. The higher the number of cyclone stages, the more the heat recovered. The energy demand of a 6-stage cyclone PH is about 60 MJ/t less than demand of a 5-stage PH, and a 5-stage PH would save approximately 90 MJ/t over a 4-stage PH. The addition of a 4^{th} cyclone stage to a 3-stage PH may decrease the energy needs by 250 MJ/t, but moisture in the raw materials should not exceed 8.5%. If this is the case, a 3-stage cyclone is preferred as the thermal efficiency will not improve when an extra stage is added. The SP unit has a typical unit capacity between 300 and 4000 t/d [1, 5]. In general, a PH tower consists of 1 to 6 cyclone stages, which are disposed one above the other in a tower. The PH kiln performance can be extended using a pre-calcination technology. For the time being, kiln systems with multistage (4 to 6) cyclone preheaters and a precalciner are considered to be the state-of-the-art technology for new dry process plants. Precalciner kilns first appeared in the 1970s. The calciner is a secondary combustion device between the PH and the rotary kiln, where typically some 65% of the total fuel is burnt. In this chamber about 60%-65% of the total kiln emissions are released while limestone ($CaCO_3$) is decomposed into lime (CaO) and carbon dioxides (CO_2). The remainder of the emissions is generated from fuel combustion. As calcination is at least 90% completed when the raw meal is fed into the rotary kiln, the PC technique allows a considerable increase in clinker capacity. The average capacity of new European plants ranges from 3000 to 5000 tonnes of clinker per day. From a technical point of view however, capacities of up to 15,000 t per day are feasible. Three PH/PC kilns with a capacity of 10,000t/d are currently in operation in Asia. The addition of a PC also reduces the energy requirements. The PH/PC kiln is the most energy efficient kiln technology. Thermal energy demand for different kilns are listed in Tables 3 and 4. Other kind of kilns includes equipments for semi-dry and semi-wet processes. For semi-dry processes, the lepol kiln (300 to 2000 t/d) - where a travelling grate preheater is installed outside the rotary kiln - requires less thermal energy than a long dry kiln (300-2800 t/d). In semi-wet processes, a filter cake is produced from raw materials handling. This cake is either extruded to pellets prior to being fed to the lepol kiln or loaded into a cyclone SP/PC kiln after being dried to a raw meal in an external drier. This latter system offers both the lowest heat consumption and the highest clinker capacity (2000-5000 t/d compared to 300-3000 t/d). If wet raw materials preparation is required, a 2 stage PC with dryer (2000-5000 t cli/d) can provide the lowest thermal

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energy consumption. The wet slurry is first dried in an integral dryer crusher, after which it is fed to the PH-PC kiln. This modern process is replacing the conventional method which comprises the long wet rotary kiln (300-3600 t/d) with an internal drying/preheating system [1, 5]. An emerging technique is the **fluidised bed cement kiln (FB)**. In Japan two pilot plants with a capacity of 20 t/d and 200 t/d has been in operation since 1989 and 1996 respectively. In China a pilot kiln with a capacity of 1000 t/d is now under construction. Compared to the SP kiln with grate cooler, the FB kiln could reduce heat consumption by 10-12%, but it is not expected to serve large capacities and is not yet available for the cement industry [1, 2].

■ **Clinker Cooling –** After sintering the hot clinker is cooled by air in the clinker cooler. There are three main types of cooling technologies, namely the rotary (tube), planetary (satellite) and the grate cooler. The latter is preferred because of key advantages. The grate cooler is suited to large clinker capacities (up to 12,000 t of clinker per day). Secondly, the amount of heated cooling air, which is re-circulated back to the PH kiln ("secondary air") or to the PC kiln ("tertiary air"), is higher and the grate cooler is an efficient heat recovery system that reach heat recovery efficiency of 70%-75%. Third, grate coolers allows for lower clinker temperatures (60-80°C compared to 120-200°C) because they use an excess of cooling air, as the amount of air for cooling is larger than that needed for secondary combustion. In the grate coolers the clinker moves slowly on a travelling or on a reciprocating grate through the cooling zone which is divided into a recuperation and an aftercooling zone. Exhaust air from the aftercooling zone is either used for drying purposes, e.g. raw materials, mineral additives or coal, or leaves the system as waste air after de-dusting. In the 1980s, travelling (or 2nd generation) grate coolers were abandoned in favour of the reciprocating grate coolers because of superior heat recovery. Modern reciprocating (3rd generation) grate coolers were introduced in 1983 to use less cooling air than the conventional devices (800-1700 Nm^3/t of clinker instead of 2000 Nm^3/t). Electricity consumption of the modern grate cooler ranges from 4 to 8 kWh/t of clinker. The economical lifetime is estimated at more than 10 years [1, 2, 5]. Rotary coolers are seldom used and planetary coolers cannot be used with PC kilns as they make it difficult to extract tertiary air for combustion. ■ **Cement grinding -** The grinding of clinker with additives to produce cement requires only electricity (no heat) and accounts for about 38% of total electricity use [2]. The choice of grinding system is mainly determined by the cement type to be produced. Currently, vertical roller mills (for high mineral additions) and high pressure grinding rolls (for limited mineral additions) are state-of-the-art technologies, as they have the highest electrical efficiency (50.5 and 445 kWh/t of cement) [5].

COSTS - Data on investment and operation costs of cement production plants are available only for the entire production process. Cost as reported by as reported in IEA [3] and ECRA [2] are difficult to reconcile. It is not easy to distinguish the impact of individual technologies, systems and components (e.g. the type of kiln) on total costs. ■ **Investment Costs –** The cement industry is one of the most capital intensive industrial sectors [1, 7]. The investment cost for conventional cement production plants is estimated by the IEA [3] to be € 263 per tonne/annum of cement production capacity (2010 €). If CO_2 capture and storage (CCS) technologies are used to reduce the GHG emissions associated to the production process, then the investment cost increases to some € 558 per tonne of cement with post-combustion CO_2 capture, and to € 327 per tonne with oxy-combustion capture. These costs refer to a production plant based on the dry process, with a 5-stage preheater and precalciner kiln, an economical lifetime of 25 years, and an annual production of 1 million tonnes of cement [3]. According to ECRA [2] the investment costs of new state-of-the-art conventional plants are estimated at €130, €170 and €250 per tonne (2007 €) for production capacity of 2, 1 and 0.5 million tonnes of clinker per year, respectively. These estimates are to be intended as overnight costs, with no account for inflation and possible impact of flexible mechanisms for GHG emissions reduction (emission trading, clean development mechanisms, joint implementation). Technology learning is estimated to reduce the investment cost by 1% per year but only for new technologies (e.g. for CCS). The financial calculations refer to two reference plants with performance same as the average performance of the 844 cement plants collected in the GNR database. The first Reference Plant represents an existing plant, with performance based on weighted average values derived from the GNR database, whereas the second Reference Plant represents a new, state-of-the-art cement plant, with performance based on the 20% percentile data. The term "state-of-the-art" means an updated technical equipment according to the expected developments in thermal and electrical energy efficiency, CO_2 capture and storage, reduction of clinker content in cement, and use of waste and biomass fuels to maximise the abatement of pollutants and minimise the costs. For example, in the 1st reference plant, it is

Tab. 3 - Thermal energy consumption for dry kilns

Kiln type	BREF [1]	CSI GNR [6]	Cembureau [5]	IEA [4]
Dry kilns with PH and PC (GJ/t)				
3-6 stages	3-3.95	3.4	2.9-3.2	2.9-3.1
Dry kilns with PH only (GJ/t)				
1-4 stages	3.1-4.2	3.7	3.1-3.5	3.3-4.2

Tab. 4 - Thermal energy consumption for different kinds of kilns. (GJ/t)

Kiln type	BREF [1]	CSI GNR [6]	Cembureau [5]
Long dry	< 5.0	4.49	3.6-4.5
Long wet	5.0-6.4	6.34	5.0-7.5
Lepol semidry / semiwet	3.3-5.4	3.85	semidry 3.2-3.6 semiwet 3.6-4.5
2 stage PC with dryer (wet)			4.5-5.0
3-4 stage SP&PC with dryer (semiwet)			3.4-3.6

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assumed that the proportion of fossil fuels, waste and biomass fuels is 90%, 7% and 3% whereas in the 2nd reference plant the proportions are 67%, 23% and 10%, respectively [2]. ■ **Operation Costs** - The cement production is an energy intensive process, with the energy accounting for between 20% and 40% of the total operation costs [1, 4, 7]. Considering a 25-year lifetime and a 5-stage preheater and precalciner kiln, the operational costs are estimated at €36, €66 and €45 per tonne of cement, for a conventional plant, for a plant with post-combustion capture, and for a plant with oxy-combustion capture, respectively. The operation costs include fixed operation cost (FOM) and variable operation costs (VOM). The latter include fuel costs, electricity costs and other variable operation costs [3]. For an annual production of 2 million tonnes of clinker, the operational cost amounts to € 32 per tonne of clinker (€ 2007) from a new installed state-of-the-art cement plant, and to €29 per tonne of clinker for an average existing plant. These figures include fuel (coal) costs of €70/t and electricity cost of €80/MWh, and no deprecation,. For an existing plant and a state-of-the-art plant, the CO_2 emissions are 679 and 600 kg per tonne of cement, respectively. The clinker to cement factor is 78% and 71%, the thermal energy consumption is 3690 and 3210 MJ per tonne of clinker, the electricity consumption is 111 and 89 kWh per tonne of cement, respectively [2]. ■ **Overall cost comparison and CCS –** An economic comparison between a conventional production plant and two plants equipped with the CCS techniques (i.e. post-combustion and oxy-combustion) is reported in IEA [3]. The evaluation is based on a dry process plant with a 5-stage preheater and precalciner kiln, an economical lifetime of 25 years, an annual production of 1 million tonnes of cement (910.000 tonnes of clinker), a discount rate of 10%, a load factor of 90%, and emission trading CO_2 price (ETS) of €25/tCO_2, coal price of €2.5/GJ and petroleum coke price of €2.34 /GJ. The assessment suggests (Figure 4) a total production cost (i.e. capital plus FOM and VOM costs) of €66, €129 and €82 per tonne of cement for (respectively) a plant without CCS, a plant with post-combustion CCS, and a plant with oxy-combustion CCS. Post-combustion capture is the most expensive CCS technology because of the high capital cost, but the associated ETS cost is the lowest one as the amount of emissions is lower (770, 177 and 374 kg CO2 per tonne of cement, respectively, with reduction of 77% for post-combustion and of 52% for oxy-combustion), thus the emissions avoided are higher. In the oxy-combustion, the CO_2 emissions are captured only from the precalciner (not from kiln, cooler, or raw mill).

POTENTIAL & BARRIERS –

■ **Thermal energy demand –** According to the GNR database [2], the thermal energy demand in the cement production process (i.e. the annual global average) decreased from 3605 MJ per tonne of clinker in 1990 to 3382 MJ/t in 2006. No breakthrough is expected to cause a significant decrease in thermal energy consumption in the future, but wet, semi-wet, semi-dry or long kilns will no longer be utilized, unless moist raw materials are the only feed materials available. Based

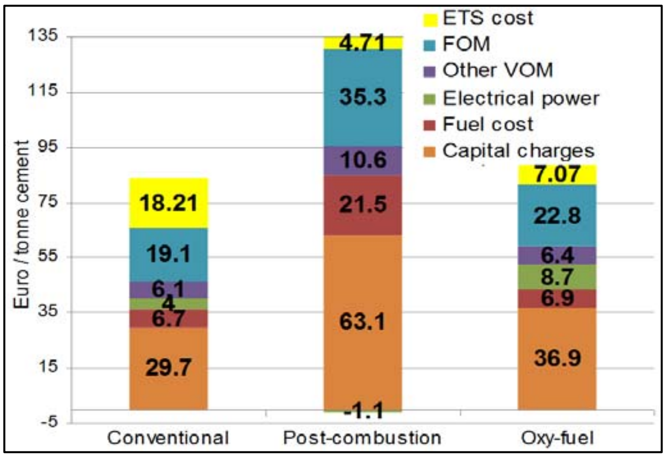

Fig. 4 - Production and ETS costs [3]

on these assumptions, the thermal energy demand is expected to decline to 3300-3400 MJ/t of clinker in 2030, and to 3200-3300 MJ/t in 2050. However, if CCS will be used, the thermal energy consumption will be higher [2]. ■ **Electricity demand –** Modest reductions have been recorded for the electricity consumption (i.e. the annual global average) that decreased to a limited extent from 115 kWh/t of cement in 1990 to 111 kWh/t in 2006. This small decrease is due to environmental requirements that need additional electrical energy. Based on these assumptions, the electricity demand in plant without CCS is projected to decline to 105 kWh/t of cement in 2030, and to 95 kWh/t in 2050. If CCS will be implemented, power consumption will increase significantly by 50% to 120% on plant basis [2, 8]. Assuming the implementation of up to 20% of cement capacity with CCS in 2030 and up to 40% in 2050, the electricity demand of a cement plant is expected to increase to 115-130 kWh/t of cement in 2030; and to115-145 kWh/t in 2050 [2]. ■ **Carbon capture and storage (CCS)** could enable up to 95% reduction of CO_2 emissions from cement production. At present, none of the three basic CCS technologies (post-combustion, oxy-combustion and pre-combustion) is ready for industrial use and no pilot plant has been implemented (only feasibility studies are available). While pre-combustion CCS is not applicable to the clinker process as it implies fundamental changes of the combustion process, post-combustion and oxy-combustion CCS can be candidates for the cement industry. Post-combustion capture could be used for new cement kilns as well as for retrofitting existing kilns, whereas oxy-combustion would only be available for new cement kilns. Among post-combustion CCS technologies, the chemical absorption technology seems to be the most appropriate. In the long-term, membrane technologies could also be an interesting option. Carbonate looping processes could be a candidate as well. Other post-combustion technologies, e.g. physical absorption or mineral adsorption, seem to be less promising. ■ **New low-carbon cements [4a] –** A number of new low-carbon or carbon-negative cements are currently being developed by start-up companies that expect to build pilot plants in 2010/11. The mechanical properties of these novel cements are similar to those of

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regular Portland cement. The necessary geological resources for the raw material feedstock are available on all continents. **NOVACEM** cement is based on magnesium oxide (MgO) and special mineral additives. It offers the prospect of lower-carbon cement through the use of an innovative production process which can use a variety of non-carbonate-based feedstocks and a novel cement composition that accelerates the absorption of CO2 from the environment by the manufactured construction products. **CALERA** cement is a mixture of calcium and magnesium carbonates and calcium and magnesium hydroxides. Its production process involves bringing sea-water, brackish water or brine into contact with the waste heat in the flue gas of power stations. **CALIX'S** cement is produced by the rapid calcination of dolomite in superheated steam at about 420 °C in a reactor, with a residence time of seconds to inhibit sintering and phase separation, followed by rapid quenching. The CO2 emissions from the flash calciner can be captured using a separate CO2 scrubbing system in which waste heat is utilised to decompose mineral sorbents, the decomposed sorbents are then brought into contact with cold flue gases where the sorbents re-carbonate, capturing the CO2 (and SOX) from the flue gas. The carbonated sorbents are then recycled back to the first step where they are decomposed again and the CO2 released is captured and potentially sequestered. **ZEOBOND'S GEOPOLYMER** cement utilises waste materials of fly ash and bottom ash from power stations, blast-furnace slag from iron-making plants and concrete waste to make alkali-activated cements. The performance of such a system is dependent on the chemical composition of the source materials (including the Si/Al ratio), the concentration of sodium hydroxide (NaOH) and potassium hydroxide (KOH) chemical activators and the concentration of soluble silicates in the activating solution. Geopolymer cements have only recently been commercialised in limited facilities for demonstration purposes. They have not yet been used in applications where strength is critical. The potential for the large-scale development of geopolymer cements is likely in practice to be limited, given that the availability of reactive components, such as fly ash and slag, is limited or expensive as in the case of metakaolin. Geopolymer cements have the potential to reduce CO2 emissions because they do not rely on the calcination of calcium carbonate and because their production does not require high-temperature kilns. Another potential advantage is that geopolymer production facilities would require less capital investment than a conventional plant. The first industrial geopolymer cement plant is currently being built in Australia. The anticipated CO2 emissions are estimated to be around 300 kg CO2/t product, around half that for the production of a CEM II cement. It is estimated that geopolymer cement will initially cost around 20% more than normal cement, but that this margin could be reduced to zero in the future.

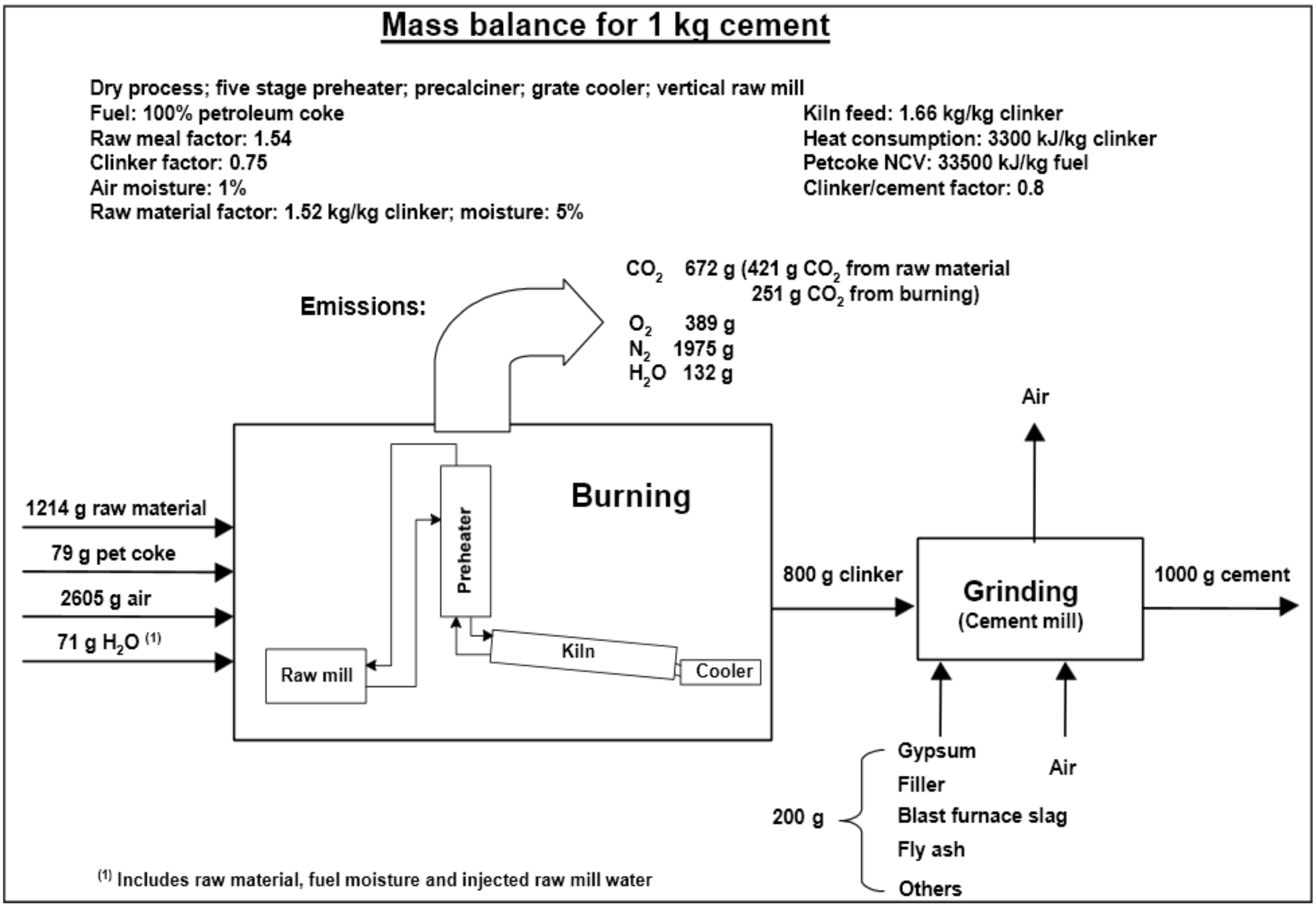

Fig. 5 - Material flows for the production of cement [1]

Table 7 - Cement Data and Figures

Technology Performance	5-6 stage PH & PC kiln	2 stage PC kiln + dryer	Lepol kiln	3-4 stage SP & PC kiln with dryer	Modern grate cooler
Raw material (t/t cli)	1.57				
Electricity (kWh/t cli)	6		12-20		4-8
Thermal energy, GJ/t cli	2.9-3.4	4.5-5.0	3.1-5.4	2000-5000	0
Air (Nm^3/t cli)	2100-2200	2100-2300	1900-2100	2100-2300	
Capacity (t clinker/d)	2000-10000	2000-5000	300-2000	2000-5000	<12000
Economic lifetime (year)	> 20				>10
Energy input	Coal, petcoke, waste and biomass fuels, lignite, fuel oil, natural gas…				
Output	Portland cement, Portland composite cement, Blastfurnace cement…				
Raw materials	Calcareous (limestone, chalk or marl) and argillaceous (clay or shale) materials, waste (e.g. blastfurnace slag, fly ash, silica fume, pozzolanas) and sometimes corrective materials (sand, waste bauxite, iron ore)				
Costs					
Plant capacity	0.48 mio.t clinker / y	1 mio.t clinker / y		1 mio.t clinker / y	2 mio.t clinker / y
Investment costs, €$_{2010}$/t clinker,	270 [2]	275 [3]		180 [2]	140 [2]
CCS Post-combustion	558 [3]				
CCS Oxy-combustion	327 [3]				
Operation costs, €/t cli)	29-32 [3]				
	Environmental Impact (Measured in existing EU kilns)				
CO_2 , kg/t clinker	800-1040 (depending on technology and average fuel input)				
Dust , kg/t clinker	0.01-0.4				
NO_x , kg/t clinker	2.1 (0.4-6)				
SO_2 , kg/t clinker	0-7				
Data Projections	**Reference year 2006**	**2030**		**2050**	
Electricity, kWh/t cem.					
Conventional	111	105		95	
With CCS		115-130		115-145	
Th. energy, GJ/t clinker	3.38	3.3-3.4		3.2-3.3	
	Substitution waste and biomass fuels, %				
Global level		30		35	
Developed regions		50-60		50-60	

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