

# **Energy, environmental and greenhouse gas effects of using alternative fuels in cement production**

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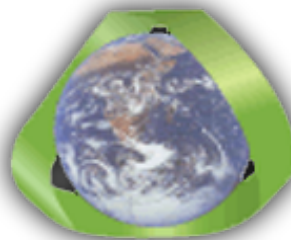
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## EXECUTIVE SUMMARY

Cement is by far the most widely used man-made material. The global cement industry produces about 3.3 billion tonnes of cement annually. Cement production is energy intensive, with about 200 kg of coal used per tonne of cement. Also, the cement industry generates about 5% of global greenhouse gases (GHG). In order to reduce the use of fossil fuels and GHG emissions, some cement producers have started to use alternative fuels (AF) mostly derived from combustible wastes that cannot be recycled economically. The objective of this study was a quantitative analysis of the energy, environmental and greenhouse gas effects of replacing fossil by alternative fuels in cement production. The use of AF was examined with a focus on this practice at two cement plants, one in the U.S. and the other in Mexico.

The results of the study are described in this thesis and can be summarized as follows:

1. The use of AF in the U.S. cement industry increased from 28 million GJ in 1993 to 58 million GJ in 2011, corresponding to an increase of AF use from 8.7% to 20.9% of the total energy consumption.
2. One of the alternative fuels used in the cement industry is a mixture of shredded non-recycled plastics and paper and is called “Engineered Fuel” (EF). Since EF contains biogenic materials, its use helps to decrease CO<sub>2</sub> emissions from cement production. For example, in 2001, when about 0.67% of the energy used by the cement industry was provided by EF and assuming that the biomass energy content of the EF is 45%, the CO<sub>2</sub> emissions of the U.S. cement industry decreased by nearly 0.32%.
3. The use of EF in the cement industry effectively increases the total waste-to-energy (WTE) capacity of the U.S. For example, in 2011, when 0.7 million tonnes of EF were used as fuel in cement production, the corresponding amount of MSW that was diverted from landfills was about 1.4 million tonnes, thus increasing the effective WTE capacity of the U.S (26.6 million tonnes) by 5.2%; also, about 0.28 million tonnes of WTE ash were incorporated in the cement clinker instead of being landfilled.
4. For reasons explained in this report, the maximum amount of EF that can be used in the U.S. cement industry (67 million tonnes of cement) was estimated to be 14.6 million tonnes. If this amount of EF were to be produced and used in cement kilns, the WTE capacity of the U.S. would be

effectively increased by 29.2 tonnes, i.e., by 110% of the current U.S. WTE capacity of 26.6 million tonnes.

5. A critical review of the literature showed that the dioxin emissions of cement kilns combusting alternative fuels are well below the E.U. and U.S. standards. The case study of Plant 2 showed the Hg emission measured was 0.000014 mg/Nm<sup>3</sup>, i.e., one thousand times lower than the standard of 0.05 mg/Nm<sup>3</sup>. The dioxin concentration measured in the stack gas was an order of magnitude lower than the E.U./U.S. standard of 0.1 ng TEQ/Nm<sup>3</sup>.

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## 1. Introduction

This study was initiated by CEMEX, an international cement company headquartered in Mexico and with several operations around the world where different types of AF are used. The study examined the environmental and energy impacts of co-combusting alternative fuels (AF), in the U.S. and worldwide. The benefits of using AF, especially engineered fuel, in cement industry are discussed and two case studies are included: The use of AF in Plant 1 (annual capacity 2.5 million short tons) in the U.S. and the emissions of Plant 2 (annual capacity 7.6 million tonnes) in Mexico.

Cement production is the largest materials-based high-temperature process worldwide; therefore, expanded use of AF in cement kilns will reduce the use of fossil fuels and also the amount of wastes that need to be landfilled or combusted.

It is hoped that this independent study of the use of AF in the cement industry will help the cement producers in informing policymakers and the general public regarding the quantitative effects of AF use in cement production; and in planning for further adoption of AF co-combustion in the cement industry.

## 2. Cement: The major construction material

Cement is by far the most widely used man-made material. This material when mixed with water solidifies and is used to bind sand, crushed stone and other inorganic materials to form concrete, the primary material used in buildings, bridges, dams, roads and other infrastructure.

### 2.1 The cement production process

There are three main stages in the cement production process.

The first stage is the preparation of raw materials, such as limestone, clays, shale and iron ore that are mined and crushed, as necessary. The crushed raw materials are mixed in different proportions to obtain the desired composition of the feed to the cement production process. After mixing and homogenization, the raw materials are ground to a dry powder or slurry, which is called raw meal.

The second stage is the clinker production process. This process takes place in a rotary kiln fired to temperatures up to 1500 °C.

In modern practice, the raw meal feedstock flows through a preheater and/or precalciner. The resulting dry powder is fed to the kiln through a cyclone preheater. A chamber is located at the base of the preheater in which about 60% of the total kiln system fuel



requirement is supplied [3]. Consequently, about 90% of calcination of raw meal occurs before it enters into the rotary kiln [3].

Because of the introduction of preheater and precalciner, the length (and residence time of the solids) of the rotary kiln is shortened ( $L/D=10-17$ ). For comparison, the  $L/D$  ratio of wet or dry rotary kilns without preheater and precalciner is 32-35 [5].

The chemical and physical processes occur in the cement production process include drying, clay mineral and calcite decomposition, and clinkering successively. The sequence of processes that occur as the raw material is heated to clinker temperatures in different types of cement plants are summarized in Table 1 [3]. In a “wet process” plant, all the processes from drying to clinkering take place in the cement kiln. In a “preheater” plant, drying takes place in the raw mill, clay minerals decomposition in the calciner, and full decomposition and clinkering in the cement kiln. In a “precalciner” plant, clay minerals decompose in preheater while most calcite decomposes in calciner and the rest in the rotary kiln.

**Table 1 Plant types used in cement production [3]**

Chemical/physical Process Plant type	Drying	Decomposition		Clinkering
		Clay minerals 300-650 °C	Calcite 800-950 °C	
“Wet”	Kiln	Kiln	Kiln	Kiln Burning Zone
“Preheater”	Raw mill	Preheater	Kiln	
“Precalciner”	Raw mill	Preheater	Calciner/Kiln+	

+ Minor amount in kiln

The energy input required in different types of cement plant is shown in Table 2[3]. The wet process requires an input of thermal energy of 5-6 MJ/kg of clinker, while the corresponding number for the dry process is 3.4-5MJ/kg of clinker. The higher energy demand of wet process is due to the energy required for water evaporation and increased energy losses in process gas and from the outer surface of the kiln. Rotary kilns equipped both with preheater and calciner require a lower energy input of 3.1- 4.2MJ/kg of clinker.

**Table 2 Energy input for different types of cement plant [3]**

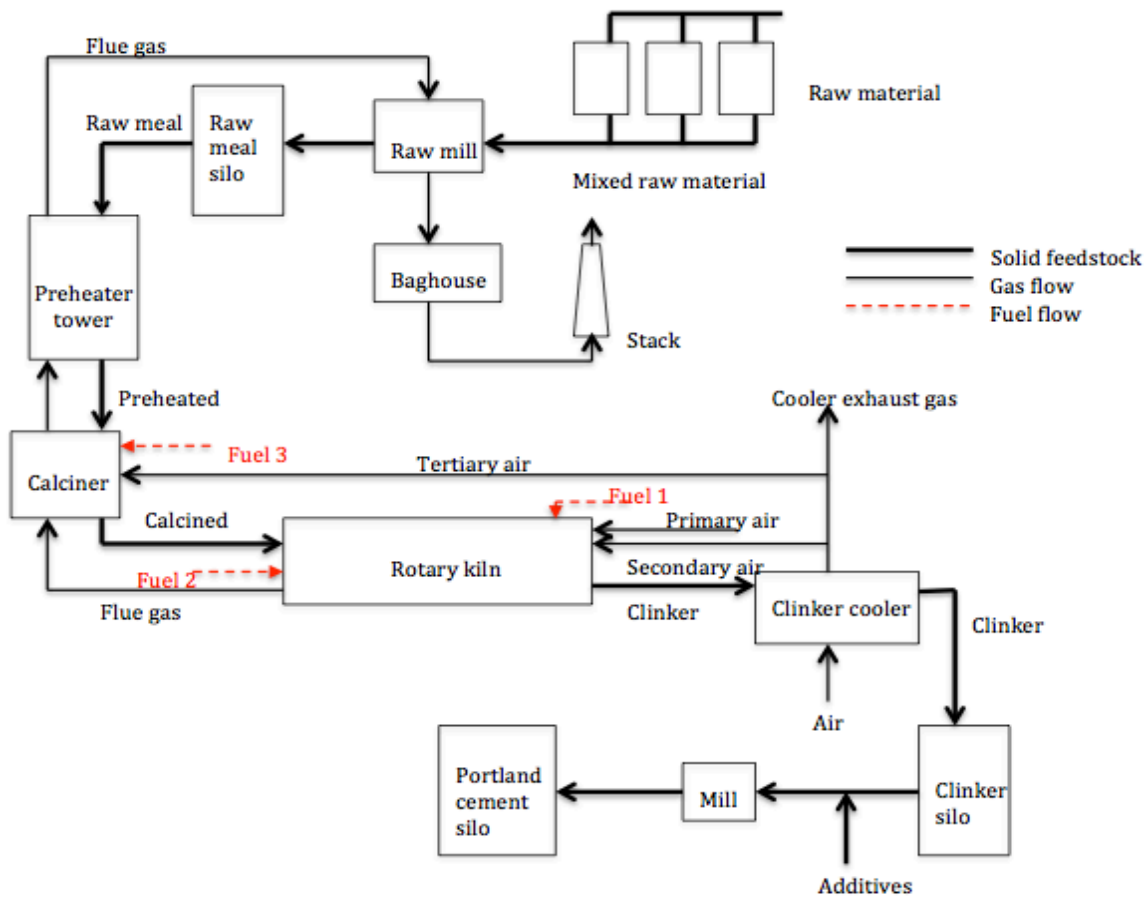
Type	Energy consumption MJ/kg clinker
Wet process	5-6
Dry process	3.4-5
Pre-calciner	3.1-4.2

After the cement clinker is produced, it is cooled in the clinker cooler. Airflow is introduced at the clinker cooler to cool down the hot clinker. There are three pathways for the hot gas from the clinker cooler. Part of the hot gas is used as the secondary air in the cement kiln. Another part of the hot gas is used as tertiary air in the calciner. The rest of the clinker cooler air is exhausted to the atmosphere.

In the third and final stage, the clinker produced in the kiln is mixed with a small amount of gypsum, a chemical agent added to control the setting time of the concrete, and then ground to fine particles, the final product is the cement powder.

## 2.2 Flow sheet of cement production

The flow sheet of cement production is shown in Figure 1. There are three material flows; solid, gas and fuel flow. The solid flow shows the process from raw material to final product, as described in section 2.1. The fuel flow shows that fuel is introduced at both calciner and cement kiln. The gas flow is more complex. There are three pathways for hot gas from clinker cooler as described in section 2.1, while the process gas from the cement kiln flows through the calciner, preheater and raw mill successively, and then passes through the Air Pollution Control Devices (APCD).



## Figure 1 Flow sheet of cement production

### 2.3 Composition of cement

As shown in section 2.1, the final cement product is produced by grinding Portland cement clinker that consists mainly of tricalcium silicate (Alite), Dicalcium silicate (Belite), tricalcium aluminate, and calcium aluminoferrite. A typical composition of cement is shown in Table 3.

**Table 3 Typical composition of cement [3]**

	Clinker*		Cement*
	Black: %	White: %	Grey: %
SiO <sub>2</sub>	21.7	23.8	19-23
Al <sub>2</sub> O <sub>3</sub>	5.3	5	3-7
Fe <sub>2</sub> O <sub>3</sub>	2.6	0.2	1.5-4.5
CaO	67.7	70.8	63-67
MgO	1.3	0.08	0.5-2.5
K <sub>2</sub> O	0.5	0.03	0.1-1.2
Na <sub>2</sub> O	0.2	0.03	0.07-0.4
SO <sub>3</sub>	0.7	0.06	2.5-3.5+
LOI	-	-	1-5.0+
IR	-	-	0.3-5.0+
Free lime	1.5 <sup>^</sup>	2.5 <sup>^</sup>	0.5-1.5

\* Cement-usual range excluding minor additional constituents; clinkers - examples used in text.

+ Upper limits in BS EN 197- 1: 2000.

<sup>^</sup> Also included in total CaO.

LOI Loss on ignition (CO<sub>2</sub> + H<sub>2</sub>O) typically 0.8-1.8%.

IR Insoluble residue - usually siliceous and typically <1%

### 2.4 Global production of cement

In 2010, the worldwide production of cement was about 3.3 billion tonnes [4]. China is the largest cement producer (1,880 million tonnes), followed by India (210 million tonnes) and the United States (67 million tonnes). The world cement production in 2010 is shown in Figure 2.

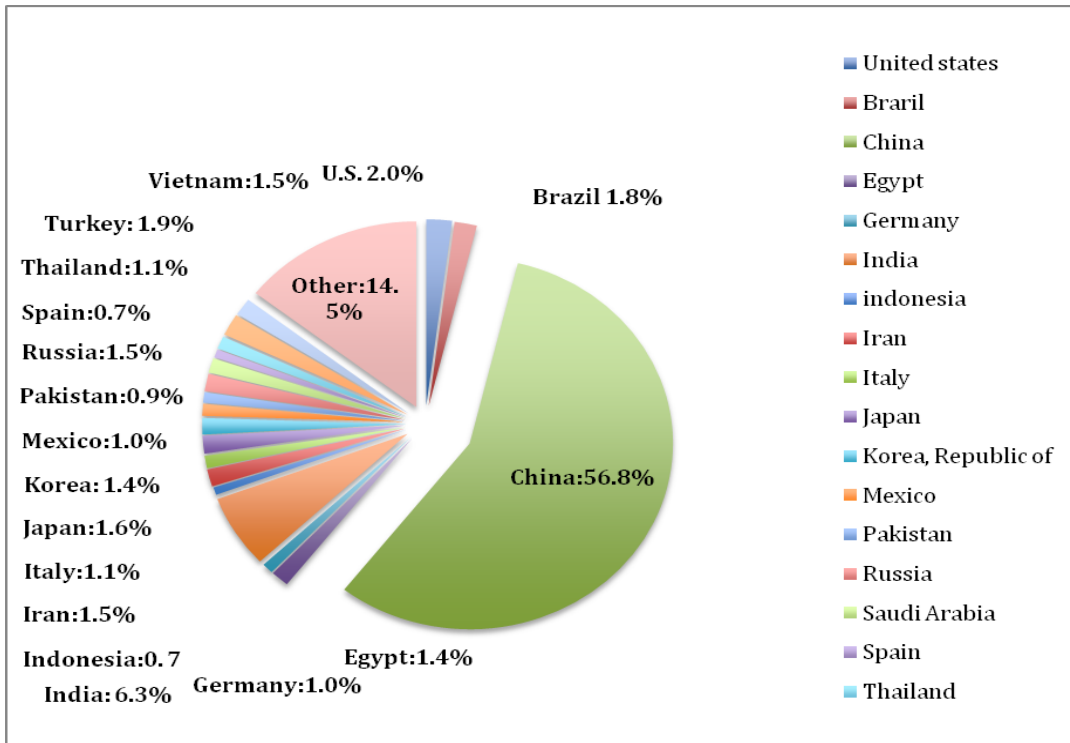


Figure 2 World cement production in 2010, total 3.3 billion tonnes [4]

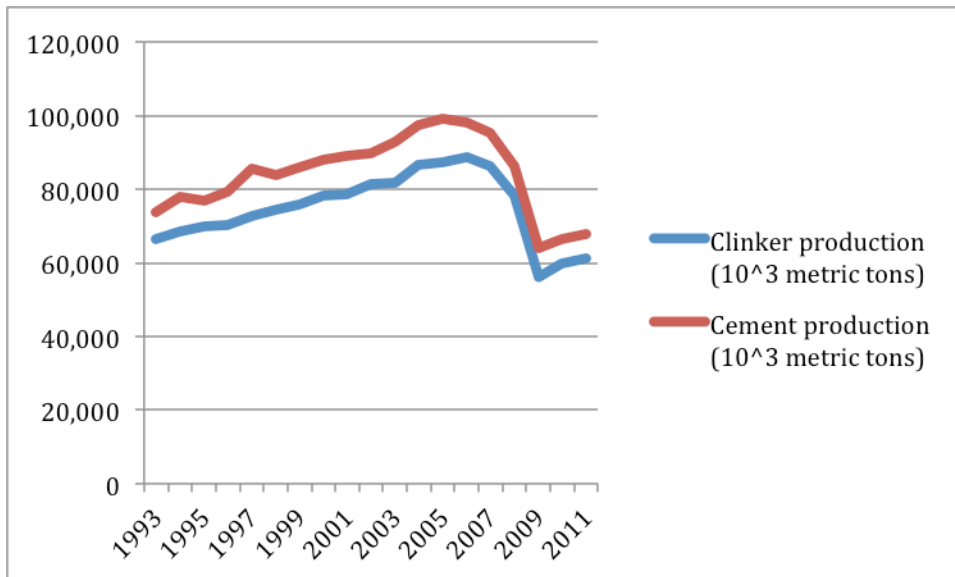
## 2.5 U.S. cement production

Table 4 shows the clinker and cement production in the U.S. during the period of 1993-2011. There are three stages for U.S. clinker and cement production. The same data are plotted in Figure 3, which shows that in the period of 1993-2005, U.S. cement production increased from 67 million tonnes to a maximum of 99.3 million tonnes in 2005. Since then, it decreased to a low of 64 million tonnes in 2009 and then increased to 67.9 million tonnes in 2011.

Table 4 U.S. clinker and cement production, 1993-2011[1]

Year	Clinker production (10 <sup>3</sup> tonnes)	Cement production <sup>1</sup> (10 <sup>3</sup> tonnes)
1993	66,597	73,807
1994	68,525	77,948
1995	69,983	76,906
1996	70,361	79,266
1997	72,686	85,582
1998	74,523	83,931
1999	76,003	85,952
2000	78,138	87,846
2001	78,451	88,900
2002	81,517	89,732
2003	81,882	92,843
2004	86,658	97,434
2005	87,405	99,319
2006	88,555	98,167
2007	86,130	95,464
2008	78,382	86,310
2009	56,116	63,907
2010	59,802	66,447
2011	61,241	67,895

<sup>1</sup> Includes cement produced from imported clinker.



**Figure 3 Clinker and cement production, U.S. 1993-2011**

### 3. Distribution of energy use in cement production

An investigation of the heat balance for different types of kilns used in the Japanese cement industry was carried out in 1994, under the sponsorship of United Nations Industrial Development Organization (UNIDO) [6]. The results are summarized in Figure 4. In this investigation, all the kiln systems had preheaters but only some had a calciner. In total, there are 43 kilns without calciner and 8 kilns with calciner. All the numbers shown in Figure 4 are the average values of thermal input or output for the two categories.

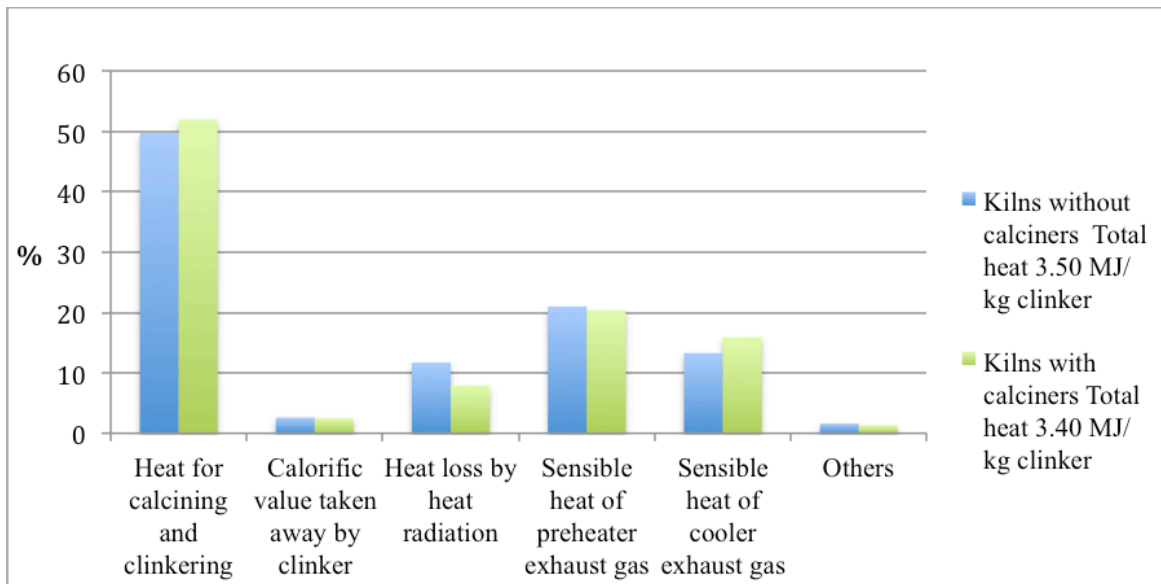


Figure 4 Distribution of heat output in different types of kilns [6]

Several conclusions can be drawn from the table above.

1. The introduction of calciner to kiln system decreases the heat demand of cement production in some degree, from 3.51MJ/kg clinker to 3.4 MJ/kg clinker. The decrease in heat demand is mainly from the decreased heat loss by heat radiation. In the calciner kiln system, the length of rotary kiln is shortened and the surface area of the rotary kiln decreases. Consequently, the heat loss by rotary kiln's heat radiation decreases.
2. The heat for calcining and clinkering is the largest heat output (about 50% of the total heat input), followed by the sensible heat of preheater exhaust gas (about 20% of the total heat input) and the sensible heat of cooler exhaust gas (about 14% of the total heat input).

### 4. Use of AF in the cement production

As mentioned before, cement production is an energy-intensive process. Worldwide, coal is the predominant fuel burned in cement kilns. Global energy- and process-related carbon dioxide (CO<sub>2</sub>) emissions from cement manufacturing are estimated to be about 5% of global CO<sub>2</sub> emissions [7]. Industrialized countries have over 20 years of successful experience. The world pioneers in this practice are Netherland and Switzerland, with national substitution rate of 83% and 48% respectively [7]. In the U.S., cement plants usually get 20-70% of their energy input from AF [7].

The alternative fuels used in cement industry include but are not limited to plastics, refuse-derived fuel (RDF), scrap carpet, scrap tires, automobile shredder residue, Bio-solids, waste oil and waste solvents.

#### **4.1 Benefits from using AF**

There are many benefits from using AF in the cement production.

The most direct benefit is making use of the embodied energy in AF to replace fossil fuels.

Another benefit of AF substitution is a reduction in CO<sub>2</sub> emissions from cement production. The cement industry is responsible for 5% of global CO<sub>2</sub> emission, nearly 50% of which are due to the combustion of fossil fuels.

Also, no further treatment of ash residuals is in need when AF is burnt in cement kilns.

Any ash residuals, if produced, are incorporated into the clinker. On the contrary, the ash residuals from waste WTE is usually further stabilized and/or disposed.

#### **4.2 Effect on emissions from using AF**

Through the usage of AF, cement manufactures can play an important role in sustainable energy and waste management. However, it should be kept in mind that combusting AF in cement kilns should be managed properly from the environmental perspective. The emissions of concern and frequently mentioned are heavy metals and dioxins and furans, as discussed below.

##### **4.2.1 Heavy metal**

The E.U. and U.S. standards for cement kilns are discussed in Section 9.2. For example, the E.U. standard for mercury is 0.05 mg/Nm<sup>3</sup> for stack gas, which is the same as for waste-to-energy plants. As shown in Table 31, the Hg emission of the case study of Plant 2, when AF was burnt, was 0.000014 mg/Nm<sup>3</sup>, one thousand times lower than the standard of 0.05 mg/Nm<sup>3</sup>. Several papers in the literature [8,9,10] confirm that the heavy metals contained in the raw materials and fuels used in cement production are either incorporated into the clinker, or contained in the Air Pollution Control (APC) system. A

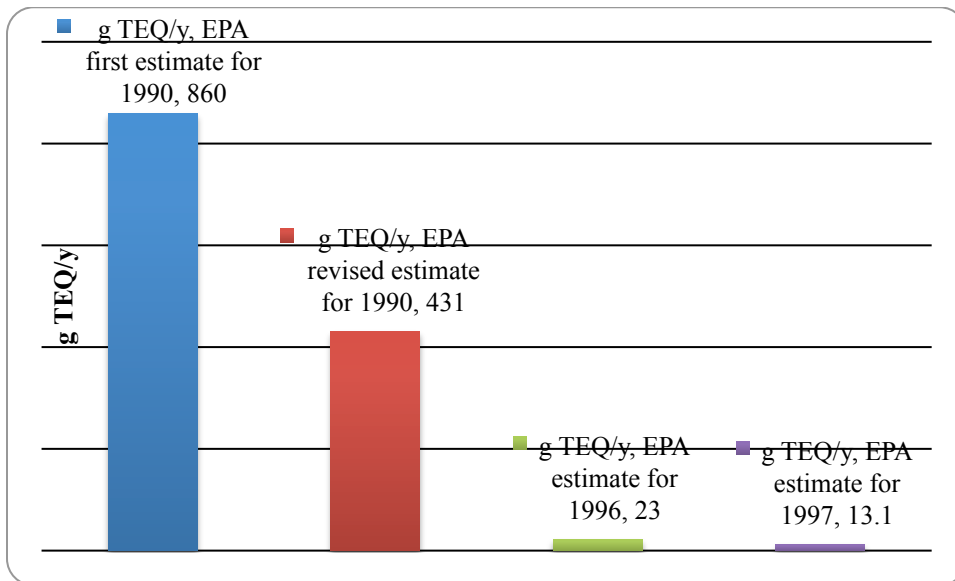
study testing the leaching ability of heavy metals contained in clinker when exposed to acidic conditions using EPA's toxicity characteristic leaching procedure showed that cadmium was the only heavy metal that could be detected in the environment, and at a level below regulatory standards [11]. The literature [8, 10] also showed that little difference of heavy metal emissions existed between plants burning only fossil fuels and those co-incinerating AF.

#### 4.2.2 Dioxins and furans

Dioxins have a potential to form in the presence of chlorine in the fuel or raw materials for cement production. However, the extremely high temperature and long residence time provided in clinker production are not conducive to dioxin formation [12]. Limiting the concentration of organics in the raw material mix, and quickly cooling the exhaust gases in wet and long dry kilns also prevent the formation of dioxins [8,12].

As shown in Table 31 for the case study of Plant 2, the highest dioxin concentration measured in the stack gas was 0.0076 ng TEQ/Nm<sup>3</sup> vs. the E.U. standard of 0.1 ng TEQ/Nm<sup>3</sup>.

A significant decrease by about 97% in U.S. dioxin emissions from hazardous waste co-incineration in cement kilns was achieved between 1990 (431 g TEQ/year) to 1997 (13.1 g TEQ/year). These results are shown graphically in Figure 5.



**Figure 5 U.S. EPA PCDD/F contribution estimates from cement kilns co-incinerating hazardous waste [13]**



A report published by the World Business Council for Sustainable Development in 2006 (WBCSD; ref. 13) included nearly 2200 dioxin emissions data from early 1990s to 2005, worldwide. The data was collected from both wet and dry kilns co-incinerating a wide range of wastes in cement production process (Table 5).

**Table 5 Summary of reported dioxin concentrations in clinker off-gas [13]**

Country	Use of AFR or not	Concentration of <sup>a</sup> PCDD/F in ng TEQ/m <sup>3</sup>	Number of data
Australia	Yes	0.001-0.7	55
Belgium	Yes	<0.1	23
Canada	Yes	0.0054-0.057	30
Chile	Yes	0.0030-0.0194	5
Colombia	Yes	0.00023-0.0031	3
Denmark	Yes	<0.0006-0.0027	?
Egypt	Yes	<0.001	3
Europe	Yes	<0.001-0.163	230
Germany 1989-1996	Yes	0.02	>150
Germany 2001	Yes	<0.065	106
Holcim 2001	Yes	0.0001-0.2395	71
Holcim 2002	Yes	0.0001-0.292	82
Holcim 2003	Yes	0.0003-0.169	91
Heidelberg	Yes	0.0003-0.44	>170
Japan	Yes	0-0.126	164
Lafarge	Yes	0.003-0.231	64
Mexico	Yes	0.0005-0.024	3
Norway	Yes	0.02-0.13	>20
Philippines	Yes	0.0059-0.013	5
Poland	Yes	0.009-0.0819	7
Portugal		0.0006-0.0009	4
RMC	Yes	0.0014-0.0688	13
Siam	Yes	0.0006-0.022	4
South Africa	(Yes)	0.00053-0.001	2
Spain	Yes	0.00695	89
Spain CEMEX	Yes	0.0013-0.016	5
Spain Cimpor	Yes	0.00039-0.039	8
Taiheiyo	Yes	0.011	67
Thailand	Yes	0.0001-0.018	12
UK	Yes	0.012-0.423	14
Uniland		0.002-0.006	2

USA <sup>b</sup>	Yes	0.004-~50	~750
Venezuela	Yes	0.0001-0.007	5
Vietnam		0.0095-0.014	3

<sup>a</sup> The numbers are either given as the range or the mean value

<sup>b</sup> The high numbers from the USA is from measurements done in the early 1990s; the number of measurement is approximate.

The WBCSD report also noted that no big difference for dioxin emissions could be found when alternative fuels are burnt in the cement production process than when only conventional fossil fuels are burnt [13].

In 2005, United Nations Environment Programme (UNEP) put forward the emission factors for PCDD/PCDF emissions from cement kiln. According to UNEP, the emission factors are based on kiln type, air pollution control devices (APCD) and the temperature of APCD; instead of whether AF being burnt in cement kilns or not [14].

**Table 6 Emission factors for PCDD/PCDF emissions from cement kiln [14]**

Classification	Emission factors- $\mu\text{g TEQ/t}$ of Cement
Shaft kilns	5.0
Old wet kilns, ESP temperature $>300^{\circ}\text{C}$	5.0
Rotary Kilns, ESP/FF temperature $200-300^{\circ}\text{C}$	0.6
Wet kilns, ESP/FF temperature $<200^{\circ}\text{C}$	0.05
Dry kilns with preheater/precalciner, $T<200^{\circ}\text{C}$	0.05

To compare the emission factors put forward by UNEP with the dioxin emissions limit of  $0.1\text{ng TEQ/Nm}^3$ , a conversion of the emission factors was done, by considering 1 tonne of cement produced and  $2000\text{ Nm}^3$  of stack gas/tonne. The emission factors after conversion are shown in Table 7.

**Table 7 Emission factors for PCDD/PCDF emissions from cement kiln after conversion**

Classification	Emission factors- $\text{ng TEQ/Nm}^3$
Shaft kilns	2.5
Old wet kilns, ESP temperature $>300^{\circ}\text{C}$	2.5
Rotary Kilns, ESP/FF temperature $200-300^{\circ}\text{C}$	0.3
Wet kilns, ESP/FF temperature $<200^{\circ}\text{C}$	0.025
Dry kilns preheater/precalciner, $T<200^{\circ}\text{C}$	0.025

Table 7 shows that the modern kilns, equipped with preheater/precalciner, operate at well below the E.U./U.S. dioxin emission limit of 0.1ng TEQ/Nm<sup>3</sup>.

### 4.3 Limits for AF use to replace fossil fuels in cement production

The maximum amount of chlorine tolerated in the total feed to the kiln is 0.7% Cl. Higher amounts result in the excessive formation of salts that are volatilized in the kiln and then solidify and can clog the following unit (in the direction of gas flow) of the calciner. This section discusses the corresponding upper limit of AF that can be used to replace fossil fuels in cement production.

The chlorine contents of different fuels were compiled and are shown in Table 8. This data was collected from different sources and small discrepancies were noted. Coal and petcoke have the lowest chlorine content. The chlorine content of petcoke is about 0.005-0.032%. There are high chlorine content coals (>0.3%) produced in Illinois, but the usual chlorine content of coals is in the range of 0.01-0.04%. Wood pellets (0.01-0.126 %) and tires (0.07-0.2 %) have higher chlorine content than coal and petcoke, but lower than RDF (0.36-1.29 %). MSW is reported to range from 0.3-1.56% ) but the typical range of U.S. NSW is 0.4-0.6%(0-1.558 %) and Engineered Fuel (0.74%).

**Table 8 Chlorine contents of different fuels**

Fuel type	Chlorine (%)			
Coal	0.04 <sup>[20]</sup>	0.01-0.03 <sup>[22]</sup>	0.01-0.2 <sup>[23]</sup>	0.12-0.54 <sup>[24]</sup>
Petcoke	0.005-0.032 <sup>[22]</sup>			
MSW	0.3-0.8 <sup>[20]</sup>	0-1.56 (0.726) <sup>[25]</sup>		
RDF		0.36-1.29 <sup>[26]</sup>		
Wood pellet	0.010-0.126 (0.048) <sup>[27]</sup>	0.01-0.05 (0.02) <sup>[28]</sup>		
Tires	0.07-0.2 <sup>[20]</sup>	0.15 <sup>[21]</sup>		
EF	0.74 <sup>a</sup>			

<sup>a</sup> From Plant 1, which will be discussed in section 8.

<sup>b</sup> Number in parenthesis is the mean value.

As reported in the literature [33], “no change in cement quality and no interruption in operations occurred up to a chlorine input of 0.7% of the clinker production”. As shown in Table 17 presented later in this report, the U.S. 2011 energy consumption was 4.54 MJ/kg of clinker. Using the highest reported values of chlorine content and also their heating values, one can calculate the maximum percentage of fuel that can be used in a kiln so as not to exceed the chlorine input of 0.7% CL in the cement production process. Table 9 shows that 100% use of coal, petcoke, wood pellets and tires is allowable, while the percent substitution of fossil fuel by MSW, RDF and EF is limited to the values shown in Table 9.

**Table 9 Limits for fuels use in cement industry**

Fuel type	Coal	Petcoke	MSW	RDF	Wood pellet	Tires	EF burnt in Plant 1
Chlorine (%)	0.04	0.032	1.558	1.29	0.126	0.2	0.741
Max percentage of fuel usage (%)	100	100	44.9	54.3	100	100	94.5

## 5. Methodology to calculate CO2 emissions from cement industry

The calculation methodology used in this thesis is based on the protocol of “CO2 and energy accounting and reporting standard for the cement industry, version 3” published by World Business Council for Sustainable Development (WBCSD) [29].

The following calculations focus on “absolute gross CO2 emissions”. Based on the protocol, “Absolute gross CO2 emissions are the fossil and direct CO2 emissions (i.e., excluding on-site electrical power production) from a cement plant in a given period” [29]. CO2 from biomass fuels and the biomass content of mixed fuels are regarded as climate-neutral [29]. This type of CO2 is excluded from “absolute gross CO2 emissions” and is recorded as a memo item [29]. Only two types of indirect CO2 emissions are included, from purchased electricity and clinker [29]. For detailed definitions and calculation methods, the reader is referred to the WBCSD protocol.

**Table 10 Emission sources to be reported within “gross emissions” (revised on basis of reference [29])**

<b>Emissions</b>
CO2 from raw materials
+ CO2 from conventional fossil fuels (excluding on-site power generation)
+CO2 from alternative fossil fuels (excluding on-site power generation)
+CO2 from fossil carbon of mixed fuels (excluding on-site power generation)
<b>=Gross CO2 emissions</b>
<b>=Direct emissions (excluding CO2 from on-site power generation)</b>

<b>Memo Items</b>
CO2 from biomass fuels
CO2 from biogenic carbon of mixed fuels
Indirect CO2 (bought electricity & clinker)

The protocol provides default emission factors per GJ lower heating value. The default values for conventional fuels and alternative fuels are shown in Table 11.

**Table 11 Default CO<sub>2</sub> Emission Factors for Fuels [29]**

Type	Category	IPCC default kg CO <sub>2</sub> /GJ	CSI default kg CO <sub>2</sub> /GJ	CSI default % biomass
	<b>Fossil fuels</b>			
1	Coal + anthracite + waste coal	96 <sup>a</sup>		
2	Petrol coke	97.5 <sup>f</sup>	92.8 <sup>b</sup>	
3	(Ultra) heavy fuel	77.4 <sup>c</sup>		
4	Diesel oil	74.1		
5	Natural gas (dry)	56.1		
6	Oil shale	107		
6a	Lignite	101		
7	Gasoline	69.3		
	<b>Alternative fossil fuels</b>			
8	Waste oil	73.3	74 <sup>b</sup>	
9	Tyres		85 <sup>d</sup>	27.0%
10	Plastics		75 <sup>d</sup>	
11	Solvents		74 <sup>b</sup>	
12	Impregnated saw dust		75 <sup>d</sup>	
12a	Mixed industrial waste		83 <sup>d</sup>	
13	Other fossil based wastes		80 <sup>d</sup>	
	<b>Biomass fuels</b>			
14	Dried sewage sludge		110 <sup>e</sup>	
15	Wood, non impregnated saw dust		110 <sup>c</sup>	
16	Paper, carton		110 <sup>c</sup>	
17	Animal meal		89 <sup>b</sup>	
18	Animal bone meal		89 <sup>d</sup>	
19	Animal fat		89 <sup>d</sup>	
20	Agricultural, organic, diaper waste, charcoal		110 <sup>c</sup>	
21	Other biomass		110 <sup>c</sup>	

<sup>a</sup>IPCC defaults are: 94.6 for coking coal and other bituminous coal, 96.1 for sub-bituminous coal, and 98.3 for anthracite

<sup>b</sup>Based on measurements compiled by CSI Task Force 1. See Guidance Document, Appendix 5 for details.

<sup>c</sup>IPCC default for residual fuel oil

<sup>d</sup>Best estimate of CSI Task Force 1

<sup>e</sup>=IPCC default for solid biomass fuels

<sup>f</sup>This data is from 2006 IPCC, but not included in the original "cement CO<sub>2</sub> and energy protocol, Version 3.0, CO<sub>2</sub> Emissions and Energy Inventory".

## 6. Energy use in U.S. cement production

Cement production is an energy intensive process. In the U.S., both conventional and alternative fuels are used. This chapter provides information on fuel use and energy consumption by the U.S. cement industry.

### 6.1 Fossil fuels and AF use in U.S. cement production

Table 12 shows the kinds of fossil fuels and alternative fuels (AF) used by the U.S. cement industry, in the period 1993-2011. As of 2004, a very small amount of coke from coal was burnt for cement production, with coal and petroleum coke remaining as the fossil fuels used. Both solid and liquid wastes were used in U.S. cement industry. Liquid waste was the mostly used AF, followed by tires, and other solid wastes. The use of “other solid wastes” increased from 90 thousand tonnes in 1993 to 699 thousand tonnes in 2011.

**Table 12 Fuel use in U.S. cement industry, 1993-2011[18]**

Year	Coal (10 <sup>3</sup> tonnes)	Coke from Coal (10 <sup>3</sup> tonnes)	Petroleum Coke (10 <sup>3</sup> tonnes)	Fuel Oils (10 <sup>6</sup> liters)	Natural Gas (10 <sup>6</sup> cubic meters)	Tires (10 <sup>3</sup> tonnes)	Other solid waste (10 <sup>3</sup> tonnes)	Liquid waste (10 <sup>6</sup> liters)
1993	10,034			46	668	70	90	744
1994	10,484			49	650	120	74	600
1995	8,241	455	1,475	42	1,069	158	68	885
1996	8,764	458	1,295	64	710	191	72	910
1997	9,035	351	1,288	86	672	277	68	835
1998	9,066	432	1,197	73	720	269	74	1,268
1999	9,206	343	1,622	82	653	685	816	906
2000	10,095	442	1,351	124	338	374	1,016	929
2001	10,240	420	1,370	93	397	300	320	829
2002	9,690	17	1,910	92.59	479	304	112	962
2003	9,460	3	1,980	85.4	377	387	317	910
2004	9,850		2,260	105	396	377	125	999
2005	9,490		2,350	87.3	395	405	130	1,470
2006	9,540		2,390	80.4	369	418	302	988
2007	9,200		2,360	87	344	446	296	984
2008	8,240		2,130	52.3	280	438	354	791
2009	5,450		1,490	35.6	344	313	324	784
2010	5,810		1,470	30.5	287	322	411	909
2011	6,050		1,290	53.9	381	320	699	1,100

## 6.2 Lower heating value (LHV) of fuels used in U.S. cement industry

The LHV of fuels used in U.S. cement industry are listed in Table 13. Except for natural gas and liquid waste, the units of other fuels are expressed in MJ/kg. As was shown in Table 12, the AF used are divided into three big categories: tires, other solid waste and liquid waste. Both “other solid waste” and “liquid waste” may include several different fuels and, therefore their LHV can vary widely. Until more specific LHV are available, the LHV assumed here are 18 MJ/kg and 32 MJ/liter, for “other solid waste” and “liquid waste”, respectively. For reference, the heating value of crude oil is 40-46 MJ/kg.

**Table 13 LHV of fuels used in U.S. cement industry**

Fuels	LHV (MJ/kg)
Coal	26.3[15]
Petcoke	34[15]
Tires	32.6[15]
Coke from coal	28.2 [16]
Fuel Oils	40 [16]
Natural Gas	38.2 MJ/m <sup>3</sup> [17]
Other solid waste	18
Liquid waste	32MJ/liter

## 6.3 Energy consumption in the U.S. cement industry

The conversion from amounts of fuel used to energy contributed by each fuel used in the U.S. cement industry is shown in Table 14.

**Table 14 Energy use in U.S. cement industry, 1993-2011 (in million GJ)**

Year	Energy from Coal	Energy from coke	Energy from petcoke	Energy from fuel oils	Energy from natural gas	Energy from tires	Energy from other solid waste	Energy from liquid waste	Total
1993	264			1.8	25.6	2.3	1.6	23.8	319
1994	276			2.0	24.9	3.9	1.3	19.2	327
1995	217	12.8	50.2	1.7	40.9	5.2	1.2	28.3	357
1996	230	12.9	44.0	2.6	27.2	6.2	1.3	29.1	354
1997	238	9.9	43.8	3.4	25.7	9.0	1.2	26.7	357
1998	238	12.2	40.7	2.9	27.6	8.8	1.3	40.6	372
1999	242	9.7	55.1	3.3	25.0	22.3	14.7	29.0	401
2000	265	12.5	45.9	5.0	12.9	12.2	18.3	29.7	402

2001	269	11.8	46.6	3.7	15.2	9.8	5.8	26.5	389
2002	255	0.5	64.9	3.7	18.3	9.9	2.0	30.8	385
2003	249	0.1	67.3	3.4	14.4	12.6	5.7	29.1	381
2004	259		76.8	4.2	15.2	12.3	2.3	32.0	402
2005	250		79.9	3.5	15.1	13.2	2.3	47.0	411
2006	251		81.3	3.2	14.1	13.6	5.4	31.6	400
2007	242		80.2	3.5	13.2	14.5	5.3	31.5	390
2008	217		72.4	2.1	10.7	14.3	6.4	25.3	348
2009	143		50.7	1.4	13.2	10.2	5.8	25.1	250
2010	153		50.0	1.2	11.0	10.5	7.4	29.1	262
2011	159		43.9	2.2	14.6	10.4	12.6	35.2	278

Table 15 below summarizes the energy consumption from fossil fuels and AF in U.S. cement production. The energy from AF increased from 28 million GJ in 1993 to 58 million GJ in 2011, corresponding to an increase of AF from 8.7% to 20.9% of the total energy consumption.

**Table 15 Energy from conventional fuels and AF, 1993-2011**

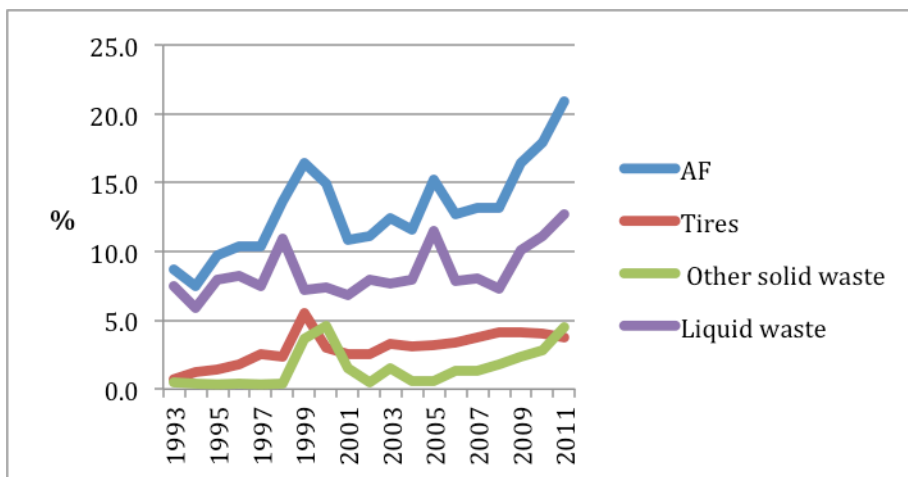
Year	Energy from conventional fuel, million GJ	Energy from AF, million GJ	Conventional fuel %	AF %
1993	291	28	91.3	8.7
1994	303	24	92.5	7.5
1995	322	35	90.3	9.7
1996	317	37	89.6	10.4
1997	320	37	89.7	10.3
1998	322	51	86.4	13.6
1999	335	66	83.5	16.5
2000	342	60	85.0	15.0
2001	347	42	89.2	10.8
2002	342	43	88.9	11.1
2003	334	47	87.6	12.4
2004	355	47	88.4	11.6
2005	348	63	84.8	15.2
2006	350	51	87.3	12.7
2007	339	51	86.8	13.2
2008	302	46	86.8	13.2
2009	209	41	83.5	16.5
2010	215	47	82.1	17.9
2011	220	58	79.1	20.9



Table 16 shows the percent share of various AF in the total energy consumption in U.S. cement industry; these results are also shown graphically in Figure 6. Liquid waste increased from 7.5% to 12.7% of the total energy. Tires are the mostly used solid wastes, its share increased from 0.7% to 3.8% of the total energy consumption.

**Table 16 Energy from AF in U.S. cement industry, 1993-2011(in percentage)**

Year	AF	Tires	Other solid waste	Liquid waste
1993	8.7	0.7	0.5	7.5
1994	7.5	1.2	0.4	5.9
1995	9.7	1.4	0.3	7.9
1996	10.4	1.8	0.4	8.2
1997	10.3	2.5	0.3	7.5
1998	13.6	2.4	0.4	10.9
1999	16.5	5.6	3.7	7.2
2000	15.0	3.0	4.5	7.4
2001	10.8	2.5	1.5	6.8
2002	11.1	2.6	0.5	8.0
2003	12.4	3.3	1.5	7.6
2004	11.6	3.1	0.6	8.0
2005	15.2	3.2	0.6	11.5
2006	12.7	3.4	1.4	7.9
2007	13.2	3.7	1.4	8.1
2008	13.2	4.1	1.8	7.3
2009	16.5	4.1	2.3	10.0
2010	17.9	4.0	2.8	11.1
2011	20.9	3.8	4.5	12.7



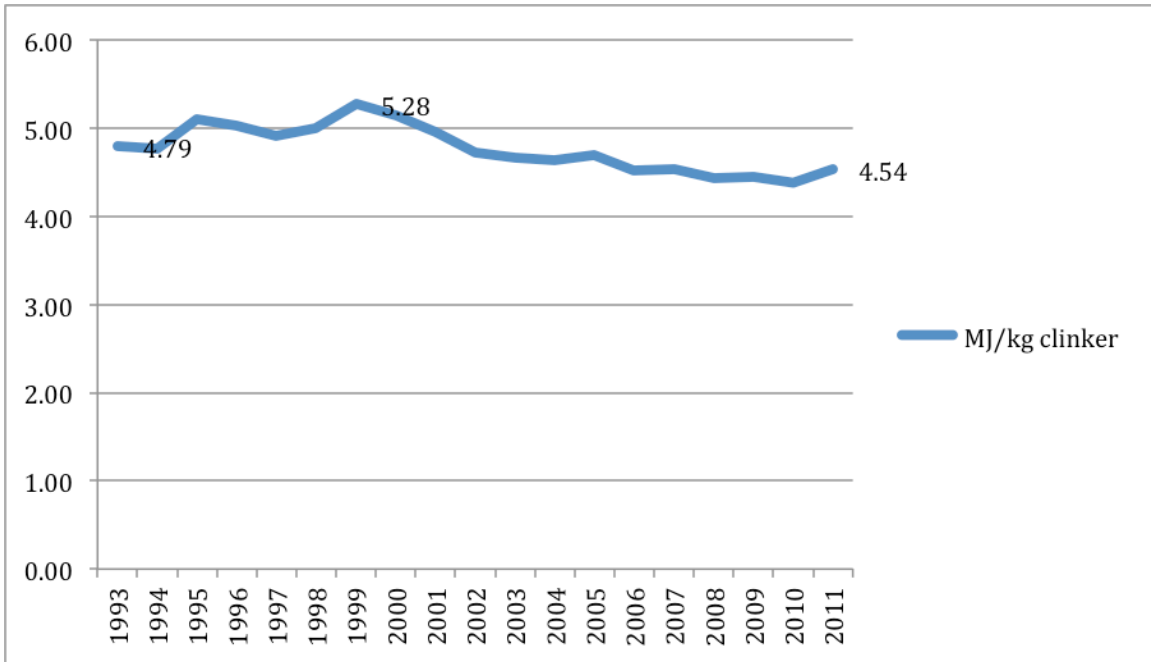
**Figure 6 The increase of using AF in U.S. cement industry, 1993-2011**

## 6.4 Specific energy consumption per kg of cement

Based on the above analysis, the energy consumption to produce clinker and cement was calculated and shown in Table 17. The change of energy consumption per kg of clinker with time is plotted in Figure 7.

**Table 17 Energy consumption to produce clinker and cement, 1993-2011**

Year	Clinker production, 10 <sup>3</sup> tonnes	Cement production, 10 <sup>3</sup> tonnes	Electricity, kWh/tonne cement	Total Energy, million GJ	Energy consumption, MJ/kg clinker	Energy consumption, MJ/kg cement
1993	66,597	73,807	142	319	4.79	4.97
1994	68,525	77,948	150	327	4.77	4.98
1995	69,983	76,906	145	357	5.10	5.27
1996	70,361	79,266	146	354	5.03	5.20
1997	72,686	85,582	145	357	4.92	5.10
1998	74,523	83,931	144	372	5.00	5.17
1999	76,003	85,952	143	401	5.28	5.42
2000	78,138	87,846	144	402	5.14	5.30
2001	78,451	88,900	146	389	4.96	5.13
2002	81,517	89,732	146	385	4.72	4.92
2003	81,882	92,843	141	381	4.66	4.84
2004	86,658	97,434	142	402	4.64	4.82
2005	87,405	99,319	139	411	4.70	4.87
2006	88,555	98,167	141	400	4.52	4.71
2007	86,130	95,464	142	390	4.53	4.72
2008	78,382	86,310	145	348	4.44	4.65
2009	56,116	63,907	147	250	4.45	4.67
2010	59,802	66,447	146	262	4.38	4.60
2011	61,241	67,895	143	278	4.54	4.74



**Figure 7 U.S. Specific energy consumption for clinker production, 1993-2011**

Figure 7 shows that the energy consumption reached a high of 5.28 MJ/kg in 1999, and decreased to 4.54 in 2011, i.e., by about 14%. The electricity for cement production did not change much and is currently about 140 kWh/tonne of cement.

From literature, the actual average energy input for cement production was 4.798 MJ/kg cement in 2005 [19]. The corresponding number in Table 17 is 4.87. The difference is only 1.5%.

## 7. Life cycle analysis of using alternative fuels in cement industry

### 7.1 “Getting the number right” Project: the decrease of CO<sub>2</sub> emissions in cement industry

“Getting the number right” (GNR) is a CO<sub>2</sub> and energy performance information system, based on emissions data from individual cement plants, under the umbrella of WBCSD. It aims to develop representative statistical information on the CO<sub>2</sub> and energy performance of clinker and cement production worldwide.

**Table 18 GNR coverage for different regions in 2010 [30]**

Region	World	U.S.	China
Coverage	25.0%	70.9%	4.9%

**Table 19 Specific heat consumption overtime (GNR participants), GJ/tonne clinker [30]**

Region	1990	2000	2005	2006	2007	2008	2009	2010	2011
World	4.26	3.75	3.69	3.69	3.69	3.67	3.59	3.58	3.56
U.S.	5.1	4.79	4.24	4.23	4.19	4.19	4.08	3.96	3.94
China	5.53	4.28	3.97	3.62	3.59	3.46	3.44	3.47	3.44

**Table 20 Average gross CO2 emissions per tonne clinker (GNR participants), kg CO2/t clinker [30]**

Region	1990	2000	2005	2006	2007	2008	2009	2010	2011
World	914	878	866	865	865	862	854	856	852
U.S.	1,030	996	943	939	937	933	919	909	901
China	1,070	951	922	888	883	869	865	869	867

Table 19 shows that the specific heat consumptions for world, U.S. and China cement industry (GNR participants) decreased during the period 1990-2011. The specific heat consumption for world decreased from 4.26 in 1990 to 3.56 GJ/tonne clinker in 2011, U.S. from 5.1 to 3.94 and China from 5.53 to 3.44. Table 20 shows that all the average gross CO2 emissions per tonne clinker for world, U.S. and China decreased during the period 1990-2011. The average gross CO2 emissions for world decreased from 914 in 1990 to 852 kg CO2/tonne clinker in 2011, U.S. from 1,030 to 901, and China from 1,070 to 867.

An interesting finding is that for GNR participants, China has better performance than U.S., in both specific heat consumption and average gross CO2 emission over years. China had both higher specific heat input and higher average gross CO2 emission than U.S. in 1990, but China ended at both lower specific heat consumption and lower gross CO2 emissions than U.S. in 2011. This finding is based on the data from GNR members, whose coverage of different regions maybe small, especially for China. For example, Table 18 shows that in 2010, GNR coverages for world, U.S. and China are 25%, 70.9% and 4.9% respectively. It is hard to say around 5% of the cement plants in China can be a good representative of the overall cement industry in China. But this comparison at least shows that China has a great potential and the capability to play an important role in decreasing CO2 emission from cement production, when China producing cement of more than half the world capacity is considered.

## **7.2 LCA of using AF in U.S. cement industry**

### **7.2.1 Avoided fossil fuels by using AF in U.S. cement industry**

As discussed before, using the energy embodied in AF can avoid the use of a large amount of fossil fuels. Here, only the effect on avoiding coal use by using AF in cement industry was calculated, and the result is shown in Table 21.

**Table 21 Avoided coal use by using AF in U.S. cement industry**

Year	AF, million tonnes	Energy from AF, million GJ	Avoided coal, million tonnes
1993	0.90	27.7	1.05
1994	0.79	24.4	0.93
1995	1.11	34.7	1.32
1996	1.17	36.6	1.39
1997	1.18	37.0	1.41
1998	1.61	50.7	1.93
1999	2.41	66.0	2.51
2000	2.32	60.2	2.29
2001	1.45	42.1	1.60
2002	1.38	42.7	1.62
2003	1.61	47.4	1.80
2004	1.50	46.5	1.77
2005	2.01	62.6	2.38
2006	1.71	50.7	1.93
2007	1.73	51.4	1.95
2008	1.58	46.0	1.75
2009	1.42	41.1	1.56
2010	1.64	47.0	1.79
2011	2.12	58.2	2.21

Table 21 shows that using AF can help save large amount of fossil fuels used in cement industry. In 2011, burning 2.12 million tonnes of AF in U.S. cement industry avoided the mining of 2.21 million tonnes of coal.

### 7.2.2 GHG effects by using AF in U.S. cement industry

In this section, the gross CO<sub>2</sub> emissions from the U.S. cement industry are compared for two cases: a) gross CO<sub>2</sub> emissions when alternative fuels are burnt to replace some of fossil fuels; and b) gross CO<sub>2</sub> emissions when only fossil fuels are burnt. The assumptions for this comparison include:

1. Apart from the use of different fuels, all other parameters related to cement production are the same in both cases, such as raw materials, electricity consumption, and energy

requirement to produce one tonne of clinker.

2. There is no clinker bought from other cement plants.
3. The effect of biofuel use is considered.

Based on the assumption that in both cases, the raw materials consumed to produce one tonne of clinker are the same, the use of different fuels is the only cause for different gross emissions (direct emissions). From Table 10, bought electricity and clinker are two main parameters for indirect emissions. Based on the assumption 1 and 2, there is no difference in indirect emissions in two cases. Then the CO<sub>2</sub> emissions difference from situation using AF and from that using only fossil fuels is determined by the difference from CO<sub>2</sub> emission factors of different fuels.

According to WBCSD CO<sub>2</sub> protocol, the CO<sub>2</sub> emissions from biofuels are not included in the gross CO<sub>2</sub> emissions and are presented as “memo item” in the final report. Then the most obvious advantage of using AF is that if biofuels are used, the CO<sub>2</sub> emissions from avoided fossil fuels, which embody the same energy as and are replaced by biofuels, are averted.

AF used in U.S. cement industry are divided into three groups: tires, other solid waste and liquid waste. Table 11 shows that AF may have either higher or lower emission factors than fossil fuel used in cement industry. For example, tyres have higher CO<sub>2</sub> emission factor than natural gas but lower than coal and petcoke. The percentage of each type of AF used is not clear, the calculation just focuses on the avoided CO<sub>2</sub> emission from using biofuels. The emissions changes from using alternative fossil fuels are not taken into consideration. According to that all the alternative fossil fuels listed in Table 11 have lower CO<sub>2</sub> emission factors than coal and petcoke and that the energy from coal and petcoke covers more than 80% of the total fossil fuels in U.S. cement industry, there is chance using alternative fossil fuels can further decrease CO<sub>2</sub> emissions from U.S. cement industry.

We will now introduce two more assumptions:

4. All of the “other solid wastes” consist of Engineered Fuel, and its biomass energy content is 45% [32], thus avoiding the CO<sub>2</sub> emissions from using fossil fuels.
5. It will be assumed that the avoided fossil fuels, by using EF, is coal and that the default emission factor for coal is 96 kg CO<sub>2</sub>/GJ.

$$\text{Energy from biofuels} = \text{Energy from other solid waste} \times 45\%$$

$$\text{Avoided CO}_2 \text{ emissions} = \text{Energy from biofuels} \times 96 \text{ kg} \frac{\text{CO}_2}{\text{GJ}}$$

$$\text{Avoided CO2 (\%)} = \frac{\text{Avoided CO2 emissions}}{\text{Total CO2 emissions from US cement industry}} \times 100\%$$

Table 22 shows that the use of biofuels can help to decrease the CO2 emissions from cement production. For example, in 2001, where 0.67% of energy for cement industry was provided by biofuels, the CO2 emissions decreased by about 0.32%.

**Table 22 Avoided CO2 emissions by using biofuels**

Year	Energy from other solid waste, million GJ	Energy from other solid waste, %	Energy from biofuels, million GJ	Energy from Biofuels, %	Avoided CO2 emissions, tonnes	Total CO2 emissions from cement industry <sup>1</sup> , tonnes	Avoided CO2, By Percentage
1993	1.6	0.51	0.7	0.23	69,984		
1994	1.3	0.41	0.6	0.18	57,542	66,700,000	0.09
1995	1.2	0.34	0.6	0.15	52,877	68,100,000	0.08
1996	1.3	0.37	0.6	0.16	55,987	68,700,000	0.08
1997	1.2	0.34	0.6	0.15	52,877	70,400,000	0.08
1998	1.3	0.36	0.6	0.16	57,542	72,100,000	0.08
1999	14.7	3.66	6.6	1.65	634,522	76,100,000	0.83
2000	18.3	4.55	8.2	2.05	790,042	77,700,000	1.02
2001	5.8	1.48	2.6	0.67	248,832	76,900,000	0.32
2002	2.0	0.52	0.9	0.24	87,091		
2003	5.7	1.50	2.6	0.67	246,499		
2004	2.3	0.56	1.0	0.25	97,200		
2005	2.3	0.57	1.1	0.26	101,088		
2006	5.4	1.36	2.4	0.61	234,835		
2007	5.3	1.37	2.4	0.61	230,170		
2008	6.4	1.83	2.9	0.82	275,270		
2009	5.8	2.34	2.6	1.05	251,942		
2010	7.4	2.82	3.3	1.27	319,594		
2011	12.6	4.53	5.7	2.04	543,542		

<sup>1</sup>Source: EPA webpage [http://www.epa.gov/ttnchie1/conference/ei13/ghg/hanle\\_pres.pdf](http://www.epa.gov/ttnchie1/conference/ei13/ghg/hanle_pres.pdf) Accessed Dec 2013.

Comparison of the corresponding numbers in columns “Energy from biofuels, by percentage” column and “Avoided CO2 by percentage” of Table 22 shows that the ratio of  $\frac{\text{Avoided CO2 by percentage}}{\text{Energy fom biofuels by percentage}}$  is about 50%.

### 7.3 Comparison between burning AF in cement plants and MSW disposal in WTE

In comparison to combustion of MSW in a WTE plant, where the bottom ash represents over 20% of the MSW feed and must be disposed, the ash generated by combustion of EF is incorporated in the clinker and, therefore, is used beneficially. To quantify these benefits, two specific situations were considered on the assumptions that a) all the “other solid waste” used in U.S. cement industry is EF, and b) that the upper limit of EF use is applied to the entire U.S. cement industry.

Two options are compared: A) use of EF in cement industry; B) use of MSW in WTE plants and disposing the ash in landfills.

Assumptions:

1. From literature [31], refuse derived fuel is approximately 42% by weight of the initial amount of wastes. Assuming that 2 tonnes of MSW are processed to produce 1 tonne of EF, then use of 1 tonne of EF in cement industry is equivalent to 2 tonnes of MSW combusted in WTE.
2. The amount of ash generated from WTE plants ranges from 15-25% by weight of the MSW processed. Here, it is assumed that the ash generated is about 20% by weight of the MSW processed, i.e., 40% by weight of EF.

The results of the comparison of options A and B are shown in Table 23. The columns of “EF burnt in cement industry, 10<sup>3</sup> tonnes” and “EF use in cement industry, %” show the amounts of EF burnt in cement industry in each year, while the “combusted MSW” is the amount of MSW disposed in WTE. On the basis of the earlier assumptions of “EF production per tonne MSW”, and “bottom ash generation per tonne MSW to WTE”, we can calculate the effects of Options A and B in the time period 2000-2011 (Table 23).

**Table 23 Comparison of using EF in cement plants vs. MSW combustion in WTE plants, in period 2000-2011**

Year	EF burnt in cement industry, 10 <sup>3</sup> tonnes	EF burnt in cement industry, %	Combusted MSW, million tonnes	Avoided MSW burnt in WTE, 10 <sup>3</sup> tonnes	Avoided MSW burnt in WTE / combusted MSW, %	Avoided ash produced by WTE, 10 <sup>3</sup> tonnes	Maximum EF use in cement industry, million tonnes	Maximum MSW avoided from WTE, million tonnes	Maximum avoided MSW/combusted MSW, %
2000	1,016	4.5	30.6	2,032	6.6	406	21.1	42.2	138
2002	112	0.5	30.4	224	0.7	45	20.2	40.4	133
2003	317	1.5	30.1	634	2.1	127	20.0	40.1	133



2004	125	0.6	31.3	250	0.8	50	21.1	42.2	135
2005	130	0.6	28.7	260	0.9	52	21.6	43.1	150
2006	302	1.4	28.5	604	2.1	121	21.0	42.0	147
2007	296	1.4	29.1	592	2.0	118	20.5	41.0	141
2008	354	1.8	28.7	708	2.5	142	18.3	36.5	127
2009	324	2.3	26.4	648	2.5	130	13.1	26.2	99
2010	411	2.8	26.6	822	3.1	164	13.8	27.5	103
2011	699	4.5	26.6	1,398	5.2	280	14.6	29.2	110

As shown in Table 23, in 2011, use of 0.7 million tonnes of EF (4.53% of total energy) in the cement industry was equivalent to adding 1.4 million tonnes of MSW to the current U.S. WTE capacity (26 million tonnes), i.e. about 5.2% of WTE capacity. If the limit of EF use in U.S. cement were to be is used in 2011, about 14.6 million tonnes of EF would be used in the U.S. cement industry. This would correspond to 29 million tonnes of MSW, thus doubling the effective WTE capacity of the U.S. to 55 million tonnes of MSW.

## 8. Case study: AF use in Plant 1

This case study refers to U.S. Plant 1 of annual production capacity of 2.5 million short tons of cement. The kiln system, Air Pollution Control (APC) system, EF production process and AF use in Plant 1 are described below.

### 8.1 Kiln system

There are two kilns in the Plant 1, denoted by kiln 1 and kiln 2. Kiln 1 is a Polysius kiln (diameter 4.6m, length 74m and 3-pier support). This kiln system has neither a formal calciner nor a tertiary air duct. It is just a riser duct where secondary burning takes place. Kiln 2 is a PYRORAPID rotary kiln (diameter 4.6m, length 54m, 2-pier support) built in 2007-08 and equipped with 5-stage preheater, PYROCLON low-NOx calciner burners, tertiary air duct and a multi-fuel PYRO-JET burner. The calciner is designed for a long retention time to ensure that alternative fuels are effectively combusted and that CO and VOC emissions are kept to the minimum.

### 8.2 Air Pollution Control (APC) system

The air pollution control (APC) system of Plant 1 includes low NOx main burner and calciner, selective non-catalytic reduction (SNCR; ammonia injection) for low NOx, and fabric filter baghouse for particulate matter (PM) control. A long retention time is provided in the calciner to ensure full combustion of the fuels used and limit CO and VOC emissions to the minimum.

### 8.3 Description of the process to produce Engineered Fuel (EF)

The EF is provided to the cement plant by a materials recovery facility in the same geographic area. In general, the process used in such facilities consists of sorting out marketable paper, plastic, metal, and glass. The residue consists primarily of non-recycled plastics (NRP) and paper fiber. It is shredded and transported to the cement plant in trucks. At an earlier time, this shredded material was extruded into a rod-like form, in order to increase its density and thus reduce transportation cost. A typical flow diagram of the EF process is shown in Figure 8.

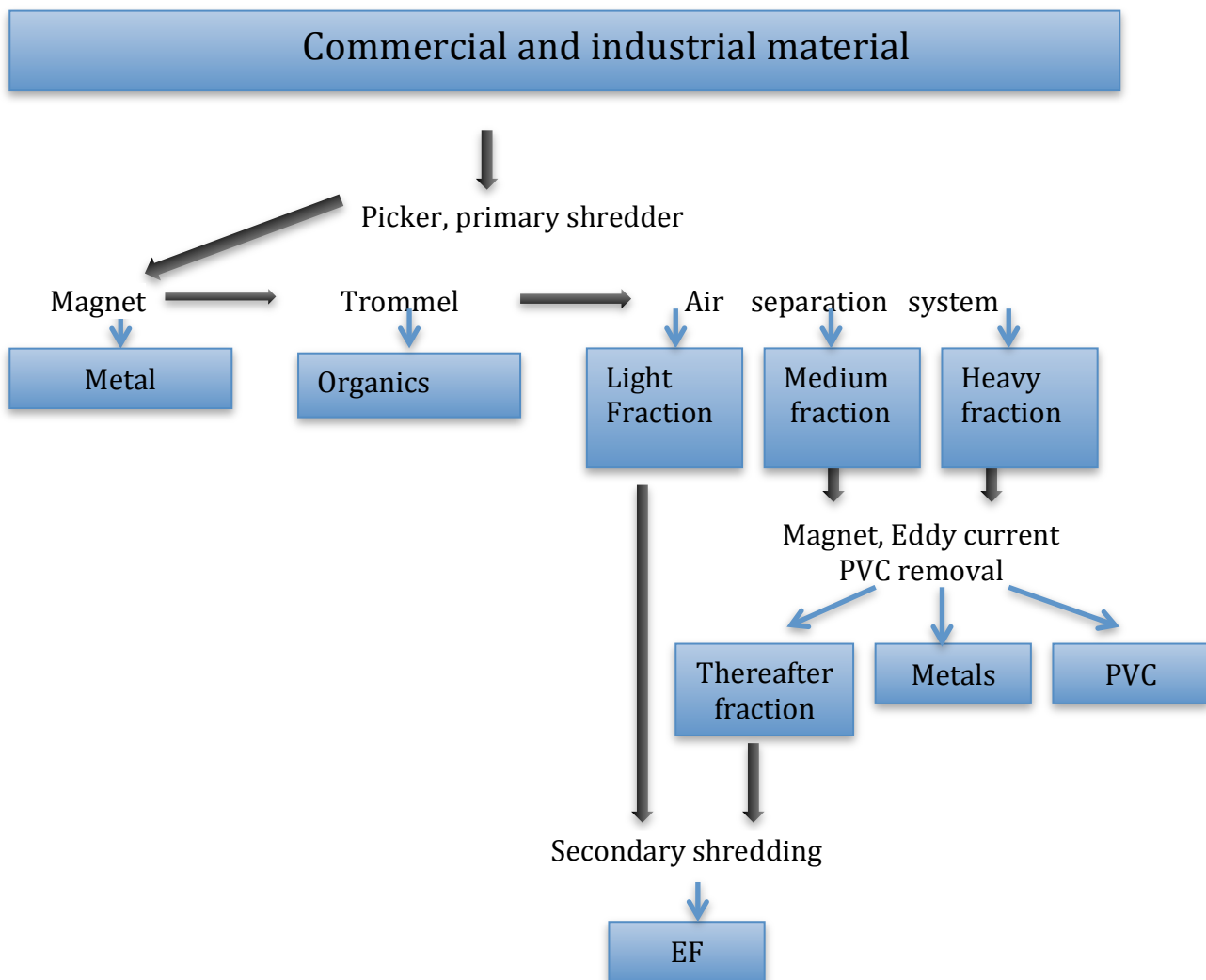


Figure 8 Process to produce EF

### 8.4 AF use in cement production

Plant 1 burns whatever alternative fuels are available in its region: Engineered Fuel (EF), wood, tires and pecan shells are the most common. Other AF includes peanut shell, rice husk, dry sewage-sludge, and animal meal. There are proper handling and dosing systems for each type of AF, in order to provide the plant with a stable feed.

Plant 1 has been increasing its use of AF with time. For example, in April, 2013, both kiln systems set an overall monthly record with of 38.9% of the energy supplied by AF, vs the old record of 37.8%. Also, in February 2013, Kiln system 2 set a new monthly record of EF use by reaching 53.5% . The compositions of AF burnt in Kiln system 2, in February and April 2013, are shown in Table 24. It can be seen that the new record was principally due to increased use of EF.

**Table 24 Composition of AF burnt in kiln 2, Plant 1**

<b>Kiln 2</b>	<b>Eng.Fuel</b>	<b>Wood</b>	<b>Tires</b>	<b>Bottom Ash</b>	<b>Pecan Shells</b>	<b>Other</b>	<b>Total</b>
<b>Feb-13</b>	15.2%	18.3%	12.2%	2.3%	0.6%	0.1%	48.7%
<b>Apr-13</b>	19.6%	18.5%	12.8%	1.9%	0.7%	0.0%	53.5%

#### 8.4.1 AF combusted in Plant 1, January- September 2013

The fuels used in Plant 1 from January to September 2013 are shown in Table 25. The corresponding energy inputs in were calculated assuming the following LHV for the different types of AF used (the heating values of the fossil fuels are the same as presented earlier):

<b>Fuel</b>	<b>LHV, MJ/kg</b>
EF	17.8
Wood	12
Pecan shells	14
Tire fluff	20
Bottom ash	0

The thermal energy contributions of the various fuels used during this period are shown in Table 26.

**Table 25 Energy consumption of Plant 1, Jan-Sep, 2013 (in GJ)**

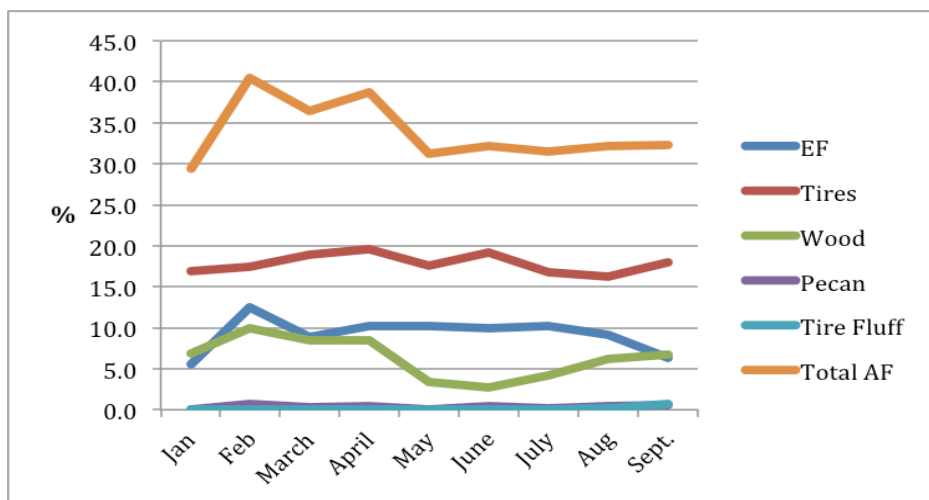
	Jan	Feb	March	April	May	June	July	Aug	Sept.	Jan-Sept
Pet coke	392,515	187,989	332,273	345,440	302,229	265,324	373,289	319,693	364,975	2,883,725
Nat Gas	65,375	64,840	38,461	16,168	40,220	37,669	32,927	60,526	31,965	388,150
Total Conv. Fuels	457,889	252,829	370,733	361,608	342,450	302,992	406,216	380,219	396,939	3,271,876

EF	36,069	53,060	51,620	60,391	50,568	44,451	60,860	50,973	37,267	445,259
Tires	109,892	74,269	110,366	115,700	87,813	85,649	99,845	91,013	105,328	879,874
Wood	44,815	42,087	49,102	50,280	17,193	12,044	25,135	34,364	39,742	314,760
Pecan	0	2,787	1,438	2,495	0	1,845	1,095	2,749	3,220	15,629
Tire Fluff								1,127	4,055	5,182
BA	0	0	0	0	0	0	0	0	0	0
Total AF	190,775	172,203	212,526	228,865	155,573	143,990	186,934	180,226	189,611	1,660,704
Total fuels	648,665	425,032	583,259	590,474	498,023	446,982	593,150	560,445	586,550	4,932,580

**Table 26 Energy consumption of Plant 1, Jan-Sep, 2013 (in Percentage)**

	Jan	Feb	Mar.	April	May	June	July	Aug	Sept.	Jan-Sept
Pet coke	60.5	44.2	57.0	58.5	60.7	59.4	62.9	57.0	62.2	58.5
Nat Gas	10.1	15.3	6.6	2.7	8.1	8.4	5.6	10.8	5.4	7.9
Total fossil fuels	70.6	59.5	63.6	61.2	68.8	67.8	68.5	67.8	67.7	66.3
EF	5.6	12.5	8.9	10.2	10.2	9.9	10.3	9.1	6.4	9.0
Tires	16.9	17.5	18.9	19.6	17.6	19.2	16.8	16.2	18.0	17.8
Wood	6.9	9.9	8.4	8.5	3.5	2.7	4.2	6.1	6.8	6.4
Pecan	0.0	0.7	0.2	0.4	0.0	0.4	0.2	0.5	0.5	0.3
Tire Fluff	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.7	0.1
BA	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total AF	29.4	40.5	36.4	38.8	31.2	32.2	31.5	32.2	32.3	33.7
Total fuels	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

The percent contribution of each AF to the total energy used in Plant 1, during January to September 2013 is plotted in Figure 9.



**Figure 9 AF burnt in Plant 1, Jan-Sep, 2013**

Figure 9 shows that the principal alternative fuel was EF, followed by tires.

#### 8.4.2 AF burnt in the Plant 1 VS overall U.S. cement industry

Two obvious differences exist between the use of AF in Plant 1 and in the overall U.S. cement industry, as presented earlier. Firstly, the overall cement industry uses liquid AF, whereas Plant 1 uses only solid AF is used.

Another finding is that the Plant 1 is much ahead of the overall U.S. cement industry with regard to the use of alternative fuels. In 2011, the AF substitution rate in the U.S. cement industry was 20.9% while Plant 1 achieved 33.7% in the period Jan-Sep, 2013. The time lag is less than two years and it is unlikely that the use of AF in the U.S. industry as a whole has increased from 20.9% to 33.7% in this period.

### 9 Case study: Analysis of Plant 2 emissions

In this part of the study, a comparison was made of the emissions of Plant 2 in a period when only petroleum coke was used with a subsequent period where alternative fuels were also used. Unfortunately, information requested from Plant 2 on the tonnages and types of fossil and alternative fuels used (during the period when the reported emissions were recorded) was not received in time to be included in this thesis. Therefore, this chapter presents only partial information.

#### 9.1 Clinker production

Clinker production data of Kiln 1, when only petcoke was used was compiled. Eight groups of daily data from year 2008 to 2010 were provided by the cement plant. The data included clinker production, amount of petcoke used, and heat input per day. Calculations were made that included petcoke heating value, petcoke used for clinker production, and heat used for clinker production. The original data and calculation results are shown in Table 27. The last row of Table 27 shows the average value for each column.

**Table 27 Clinker production when only pet coke is used (Plant 2, Kiln 1)**

<b>Date</b>	<b>Clinker production, tonnes/day</b>	<b>Pet coke used, tonnes/day</b>	<b>Reported heat input, Mcal/day</b>	<b>Calculated pet coke heating value, MJ/kg</b>	<b>Petcoke used for clinker production, kg/tonne</b>	<b>Calculated heat used for clinker production, MJ/kg</b>
<b>4-Sep-08</b>	7,213	684	5595120	34.19	94.83	3.24
<b>5-Sep-08</b>	7,210	681	5572190	34.20	94.45	3.23
<b>10-Sep-08</b>	7,150	678	5547643	34.20	94.83	3.24
<b>20-Jul-09</b>	7,117	670	5525893	34.47	94.14	3.25

<b>21-Jul-09</b>	7,161	674	5558884	34.47	94.12	3.24
<b>16-Jul-10</b>	7,208	682	5593400	34.28	94.62	3.24
<b>13-Jul-10</b>	7,210	682	5592351	34.28	94.59	3.24
<b>15-Jul-10</b>	7,205	681	5584151	34.28	94.52	3.24
<b>Average value</b>	7,184	679	5571204	34.30	94.51	3.24

Table 27 leads to several important conclusions:

- Clinker production is very steady from day to day (about 7200 tonnes/day or 300 tonnes/hr).
- Calculated heating value of petcoke is very stable (around 34 MJ/kg) and consistent with the value shown in Table 2.
- Petcoke use for clinker production is very steady, near 95 kg/tonne, corresponding to 3.24 MJ/kg.
- Plant 2, with heat input of 5571204 Mcal/day, is calculated to have a thermal input of  $5571204 \times 4.18/24$  MJ/h = 970318 MJ/h = 970318/3600 MW = 270 MW.

## 9.2 U.S. and E.U. emission standards for cement kilns

To control emissions from cement production, there are different regulations in different countries. The E.U. standards for cement kiln co-incinerating AF and also the U.S. standards for cement plants are shown in Tables 28 and 29, respectively. The original E.U. standards are based on 10% O<sub>2</sub>; in the last column of Table 28, these standards are converted to 7% O<sub>2</sub>, for comparison with the U.S. standards of Table 29.

**Table 28 E.U. standards for cement kiln co-combusting AF**

<b>Pollutants, mg/Nm<sup>3</sup></b>	<b>Original standard 10% O<sub>2</sub></b>	<b>Standard after conversion<sup>a</sup>, 7% O<sub>2</sub></b>
<b>PM</b>	30	38.19
<b>HCl</b>	10	12.73
<b>HF</b>	1	1.273
<b>NO<sub>x</sub></b>	500	636.5
<b>Cd+Tl</b>	0.05	0.06365
<b>Hg</b>	0.05	0.06365
<b>Sb+As+Pb+Cr+Co +Cu+Mn+Ni+V</b>	0.5	0.6365
<b>D/F (ng/Nm<sup>3</sup>)</b>	0.1	0.1273
<b>SO<sub>2</sub></b>	50	63.65
<b>TOC</b>	10	12.73

<sup>a</sup> Conversion from 10% O<sub>2</sub> to 7% O<sub>2</sub>:  $c_{7\% O_2} = 1.27 \times c_{10\% O_2}$

**Table 29 U.S. standards for stack gas of cement plants**

Pollutants	Unit	Existing kilns	New kilns
PM	lb/ton clinker	0.07	0.02
D/F	ng TEQ/dscm	0.2	0.2
Mercury	lb/million tons clinker	55	21
THC	ppmvd	24	24
HCl	ppmvd	3	3
NOx	lb/ton clinker		1.5
SO2	lb/ton clinker		0.4

From Tables 28 and 29, it is hard to compare E.U. and U.S. standard on cement industry. In the E.U. standards, the emission limits are usually on mg/m<sup>3</sup>. In the U.S. standards, the emission limits are based on lb/ton clinker, with regard to PM, Hg, NOx and SO<sub>2</sub>. To make the comparison possible, it is necessary to know the volume of exhaust gas generated per ton of clinker.

### 9.3 Emission data

Plant 2 emission data using only petcoke is shown in Table 30. The emission data were collected at different times, in 2008, 2009 and 2010. The units used are kg/h for PM, and mg/m<sup>3</sup> for SO<sub>2</sub>, NOx and CO.

**Table 30 Plant 2 emission data using only pet coke fuel**

		2008	2009	2010
PM	kg/h	7.42	3.99	4.57
SO <sub>2</sub>	mg/m <sup>3</sup>			
NOx	mg/m <sup>3</sup>	857.55	830.39	696.5
CO	mg/m <sup>3</sup>	151.8	237.59	546

Plant 2 emission data, when 15.9% and 16.5% of the thermal energy was supplied by AF, was collected for the days of August 8 and 9, 2012, respectively. The original data is based on 7% O<sub>2</sub> and at 25°C, 1 atm (cnbs= dry basis @ 25°C, 1 atm) and was converted to 7% O<sub>2</sub> and at standard temperature and pressure (STP) basis. The recorded emissions are shown in Table 31.

**Table 31 Plant 2 emission data when using pet coke and AF**

Original data			Data after conversion <sup>a</sup>		
Stack 2, 15.9% AF 8-Aug-12	Stack 1, 16.50% AF 9-Aug-12	unit (7% O <sub>2</sub> cnbs)	Stack 2, 15.9% AF 8-Aug-12	Stack 1, 16.50% AF 9-Aug-12	Unit (7% O <sub>2</sub> ,STP)

<b>PM<sup>b</sup></b>	1.222	0.842	kg/h	2.04	1.41	mg/Nm <sup>3</sup>
<b>SO<sub>2</sub></b>	8.63	7.79	mg/m <sup>3</sup>	9.41	8.49	mg/Nm <sup>3</sup>
<b>NO<sub>x</sub></b>	297.1	242.7	mg/m <sup>3</sup>	324	265	mg/Nm <sup>3</sup>
<b>CO</b>	388.9	325.4	mg/m <sup>3</sup>	424	355	mg/m <sup>3</sup>
<b>HCl</b>	51.86	43.39	mg/m <sup>3</sup>	56.53	47.30	mg/m <sup>3</sup>
<b>Sb, As, Mn, Ni, Se</b>	0.0147	<0.0037269	mg/m <sup>3</sup>	0.016023	<0.00407	mg/m <sup>3</sup>
<b>Cr, Pb, Zn</b>	0.00981	0.00538	mg/m <sup>3</sup>	0.0106929	0.0058642	mg/m <sup>3</sup>
<b>Cd</b>	<0.000002	0.0000067	mg/m <sup>3</sup>	<0.0000022	0.000007303	mg/m <sup>3</sup>
<b>Hg</b>	<0.000012	<0.000010	mg/m <sup>3</sup>	<0.000014	<0.000011	mg/m <sup>3</sup>
<b>PCDD/F</b>	0.00701	<0.00003	ng/m <sup>3</sup>	0.0076409	<0.000033	ng/m <sup>3</sup>

<sup>a</sup> The conversion of emission values from 7% O<sub>2</sub> cnbs to 7% O<sub>2</sub> STP: Emission<sub>STP</sub>=1.09

× Emission<sub>cnbs</sub>

<sup>b</sup> The conversion of PM emission from kg/h to mg/Nm<sup>3</sup>: 1 kg/h=1.67mg/m<sup>3</sup>. This is based on the assumptions of 2000 Nm<sup>3</sup> exhaust gas/ton of clinker and the calculated production rate of 300 ton of clinker/ hour.

A comparison was made of the emission data when only petcoke was used with the period when AF was also used. The results are shown in Table 32.

**Table 32 Plant 2 emission data**

	Pet coke only, stacks 1 and 2			AF co-combustion		
	2008	2009	2010	Stack 2 8-Aug-12	Stack 1 9-Aug-12	
<b>PM</b>	mg/m <sup>3</sup>	12.39	6.66	7.63	2.04	1.41
<b>SO<sub>2</sub></b>	mg/m <sup>3</sup>	NA	NA	NA	8.63	7.79
<b>NO<sub>x</sub></b>	mg/m <sup>3</sup>	857.55	830.39	696.5	297.1	242.7
<b>CO</b>	mg/m <sup>3</sup>	151.8	237.59	546	388.9	325.4
<b>Hg</b>	mg/m <sup>3</sup>	NA	NA	NA	<0.000012	<0.000010
<b>Cd</b>	mg/m <sup>3</sup>	NA	N	0.0007	<0.0000022	0.000007303
<b>PCDD/F</b>	ng/m <sup>3</sup>			0.0005	0.0076409	<0.000033

Discussion:

1. Table 32 shows that the emission values, except for dioxin, when AF is also used are relatively lower than the emission values when only pet coke is used. For example, when only pet coke is used, PM emission is in range of 36.66-12.39 mg/m<sup>3</sup>; while when AF is also used, PM emission is in the range of 1.41-2.04 mg/m<sup>3</sup>. It is very likely that this large reduction is due to improvements made in the Air Pollution Control system of Plant 2, between 2010 and 2012 when alternative fuels were used in place of some of the pet coke.



2. Comparison of the emission data obtained when AF was used with the E.U. standards for “kilns co-incinerating waste” of E.U. standard, shows that SO<sub>2</sub>, NO<sub>x</sub>, Hg, D/F comply with E.U. standard. In particular, the three emissions that effectively led to the MACT regulation, mercury, cadmium, and dioxins/furans are all orders of magnitude lower than the E.U. standards.

## 10. Conclusions

This study has shown that the combustion of alternative fuels in the cement kiln system is being applied widely and offers definite environmental and energy advantages.

1. The use of AF in the U.S. cement industry increased from 28 million GJ in 1993 to 58 million GJ in 2011, corresponding to an increase of AF use from 8.7% to 20.9% of the total energy consumption. In 2011, the use of about 2.12 million tonnes of various types of AF corresponded to about 2.21 million tonnes of coal.
2. One of the alternative fuels used in the cement industry, a mixture of non-recycled plastics and paper, is called “Engineered Fuel” (EF). Since EF contains biogenic materials, its use helps to decrease CO<sub>2</sub> emissions from cement production. For example, in 2001, when about 0.67% of the energy used by the cement industry was provided by EF, based on the assumption that biomass energy content of EF is 45%, the CO<sub>2</sub> emissions of the industry decreased by nearly 0.32%.
3. The use of EF in the cement industry effectively increases the total waste-to-energy (WTE) capacity of the U.S. For example, in 2011, when 0.7 million tonnes of EF was used as fuel in cement production, the amount of MSW to produce EF would be 1.4 million tonnes, thus increasing the WTE capacity of the U.S (26.6 million tonnes) by 5.2%. Also, about 0.28 million tonnes of ash from WTE would be avoided by burning 0.7 million tonnes of EF in cement production. The EF ash is incorporated into the clinker.
4. For reasons explained in this report, the estimated maximum amount of EF that can be used in the U.S. cement industry (67 million tonnes) is 14.6 million tonnes. If this amount of EF were to be produced and used in cement kilns, the WTE capacity of the U.S. would be effectively increased by 29.2 tonnes, i.e., by 110% of the current U.S. WTE capacity of 26.6 million tonnes.
5. A critical analysis of the literature showed that the dioxin emissions of cement kilns are well below the E.U. and U.S. standards. The case study of Plant 2 showed the Hg emission was 0.000014 mg/Nm<sup>3</sup>, i.e., one thousand times lower than the standard of 0.05 mg/Nm<sup>3</sup>. The dioxin concentration measured in the stack gas was an order of magnitude lower than the E.U./U.S. standard of 0.1 ng TEQ/Nm<sup>3</sup>.

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