Using Engineered Fuels as a Substitute for Fossil Fuels in Cement Production

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EXECUTIVE SUMMARY

Municipal solid waste (MSW) is inevitable and is being generated more and more globally as societies are more and more leaning towards consumerism and fast-paced lifestyles. Although governments, NGOs and even corporate businesses are raising awareness with respect to environmental concerns such as pollution, greenhouse gas emissions and resource conservation, waste generation remains very significant and, consequently, an increasing amount of wastes are discarded in landfills or even simply dumped in non-regulated waste dumps in the less developed areas of the world.

In the US, the EPA reported that 250.4 million tons of MSW were generated in 2011. This number is understated and, according to a 2013 Columbia national survey, is closer to 389 million tons. According to the EPA report, in 2011 the waste management methods were divided as follows: 34.5% was recycled or composted, 11.7% was processed in waste-to-energy power plants, and 53.8% discarded in landfills. The portion of waste of interest in this study is the landfilled portion, namely the largest fraction. Landfills have absolutely no benefit to any party or to the environment. To mention a few impacts: waste dumped takes up a lot of area that could otherwise be used for habitat or greenery, the waste overtime emits landfill gas which is 50-50% mainly CO_2 and CH_4 – the main GHG contributors – nauseous odors and possible health adverse effects may occur on surrounding communities.

The cement industry produces the most widely used construction material, requires a significant amount of fossil fuels (120 to 180 kg of coal/ton cement), and contributes up to 5% of global CO_2 emissions. The idea of making use of the non-salable waste – as a fuel fed to cement plants – instead of landfilling it, was the driving force behind this feasibility study of replacing fossil fuels with what is known as engineered fuels. Economic, environmental and operational feasibility studies are necessary to evaluate to what extent such a substitution can be done without affecting product quality, environmental impact or business growth for all parties involved. This study that

showed that extensive work is currently being done on that matter across the world. In the US specifically, of the 107 cement plants in place, more than 20% have been integrating alternative fuels (AF) to their processes. The contribution of AF in the cement industry increased from 3 to 25% between 1980 and 2013. Some experimental work conducted on actual EF samples provided to the author by two cement plants in the US and Mexico showed that engineered fuel has a heating value close to 17MJ/kg, which fits the middle-energy fossil fuels used conventionally. Sulfur and chlorine content of alternative fuels are low relatively to coal, thus resulting in another environmental improvement when the switch us made from fossil to alternative fuels. Cost-wise, although fossil fuel prices are currently decreasing, landfilling gate fees are becoming higher as landfill areas become limited, and using the waste for a better end on both sides seems to be a beneficial means of protecting the environment.

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2 BACKGROUND OF WASTE MANAGEMENT IN THE U.S

2.1 The Situation of MSW in the U.S and Waste Characterization

Municipal Solid Waste (MSW) includes but is not limited to the waste products generated by households and small businesses. In the U.S, MSW generation has been on an increase for more than 3 decades; 88.1 MMtons of waste were generated in 1960 and this number and has been continuously increasing until it reached 250.9 MMton/year in 2012 (EPA, 2012). This is equivalent to 4.38 lb waste generated per person per day.

Although work is being done to manage this waste as "cleanly" and efficiently as possible, technologies and infrastructure are still being developed to process the huge amounts of waste that are increasing at a much faster rate.

2.2 Waste Management Practices

The main waste management practices are: landfilling, recovery and WtE.

2.2.1 Landfilling

Until 2012, more than half, namely 53.8% of the total MSW generated in the U.S ended up being landfilled (EPA, 2012) – that is buried underground with minimal treatment and/or sanitary precautions – causing negative consequences on the environment and the surrounding communities. These consequences include:

1. Increased landfill capacity in the U.S (although number of landfills has decreased)
2. Increased tipping fee: average fee was $44/ton MSW landfilled in 2012
3. Environmental impacts include:
   a. Loss of land area resources;
   b. Greenhouse Gas (GHG), namely methane (CH_4) emissions: landfills were ranked 3rd largest source of CH_4 emissions in the U.S in 2011, with an estimated 103 million tons generated out of which almost 50% is recovered and combusted for energy generation;
   c. Potential leaching of hazardous substances to groundwater (CCS, 2013).

2.2.2 Material Recovery

Material recovery includes recycling and composting. It accounted for 34.5% of total MSW generated in the U.S in 2012 (EPA, 2012). Organic waste such as food and biomass are recovered through composting, plastics, metals, papers and paperboard are separated from the waste stream in Material Recovery Facilities (MRFs) and sent to respective recycling facilities, the residue (non-recyclable material, or components with no marketable value) is added to the MSW stream that goes to landfills.

2.2.3 Waste to Energy

Combustion of MSW for electricity generation has been used increasingly in the world and the U.S. Waste-to-Energy facilities generates a variety of pollutants (CO_2, heavy metals, dioxins, particulates) that contribute to impacts such as climate change, smog, acidification, asthma, and heart and nervous system damage (CCS, 2013) but are seen as an important way to reduce the volume of waste that is sent to landfill by 90%: the residual ash that results from burning MSW is approximately 10% by volume that of the feed waste burnt (75% less by weight). Controversies regarding emissions reductions and cost effectiveness of this process are being disputed and that is why the Waste-to-Energy sector in the U.S has been stagnant in the recent years. In 2012, 11.7% of the total MSW generated in the U.S was sent for incineration and energy recovery (EPA, 2012).

2.3 Waste Residue: A Potential Resource Instead of Useless Waste

Combining the waste that goes directly from collection to landfills with the residual, non-recoverable residue discarded from MRFs, large amounts of waste can be redirected towards useful purposes, while avoiding dumping them in landfills. Looking at this 'waste stream of MSW' as a valuable resource lead to the creation of 'Engineered Fuels' (EF) which results from basic treatment and processing of these residual streams into fluffs and/or pellets and then sent to be used as fuels in different industries, namely the cement production process of Portland Cement, a very energy-intensive process that is flexible with respect to types of fuels injected into its reactors.

3   THE CEMENT INDUSTRY IN THE WORLD AND THE U.S

3.1   Cement production: facts and figures

The economist described cement as 'as vital a commodity to fast-growing economies as oil or steel. No other material is as versatile when it comes to building houses, roads and big chunks of infrastructure. It is a huge business: the world's cement-makers rake in revenues of $250 billion a year. Outside China, which accounts for half of global demand and production and is mainly served by local firms, six vast international firms—Buzzi, Cemex, Heidelberg, Holcim, Italcementi and Lafarge—together have 40% or so of the market. Yet the business rarely attracts much attention' (The Economist, 2013).

Portland cement is the basic ingredient of concrete; the world's most used construction material. Figure 1 shows the production of cement in the world and the US over the 2010-2013 period. Cement production globally have been on an increase in the past decade, however, local production in the US decreased sharply from 99.3 million tons in 2005 to 63.9 million tons in 2009. It has been slowly increasing after that and reached around 77.8 million tons in 2013 (USGS, 2009; USGS 2012; USGS 2014).

Figure 1: world 2010

Yearly cement production in the and the US since
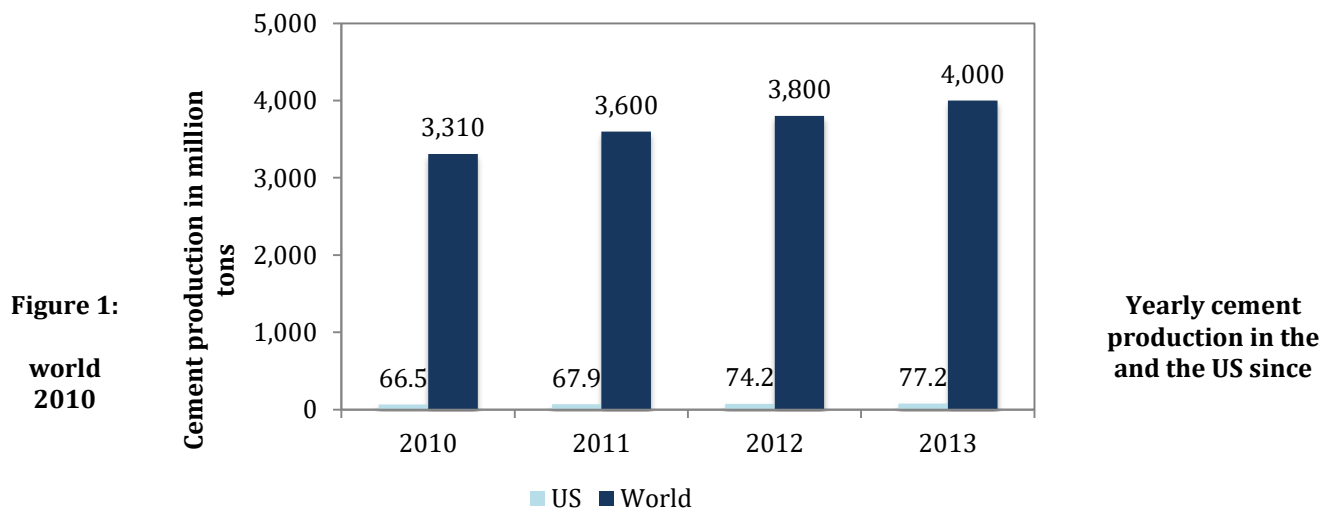
3.2   Cement production process

Cement is a fine powder, which sets when mixed with water and hardens in a few days into a strong material. It is mainly used to bind coarse aggregates and fine sand in concrete (Cement bureau, 2014).

The production of cement is a two-step process. Different processes are present and they are known as dry, wet, semi-dry and semi-wet. The main difference being whether or not the raw meal is pre-heated before entering the kiln. An overview of the process is necessary to understand where EF fits and how it is a better option than fossil fuels.

3.2.1   Different types of processes

Raw materials
The main raw materials for cement are clay and limestone. They are generally found in quarries next to which cement production plants usually stand.

Step 1: clinker production
The raw materials are crushed and homogenized and fed into a rotary kiln. The kiln - a 60 to 90 meter long (and up to 6 meter in diameter) rotating pipe - is heated by a 2000C flame inside of it and slightly inclined to allow the material to reach the other end (Cement Bureau, 2014).
The combustion fuels are usually injected in the lower end of the kiln, in a countercurrent manner. The materials continuously and slowly move from the higher end to the lower end by rotation of the kiln. As they move down they are changed into cementitious or hydraulic minerals as a result of the increasing temperature in the kiln. The most commonly kiln fuels are coal, natural gas and oil (EPA, 2010).
Four basic oxides in the right proportions make the cement clinker: calcium oxide (CaO – 65%), silicon oxide (SiO – 20%), alumina oxide (Al_2O_3 – 10%) and iron oxide (FeO – 5%). These elements combine when heated by the flame at a temperature close to 1450C and form new compounds namely ferrites, silicates and aluminates of calcium (Cement Bureau, 2014).

Production processes can be grouped in two: dry and wet processes. Both lead to the same product, but vary with respect to equipment design, method of operation and fuel consumption. The general trend for fuel consumption is a decrease in the order of processes listed.
A brief description of each process follows, taking the wet process as reference.

The **wet process** requires that raw materials are fed moist to the rotary kiln. On average an additional 33% of energy input is required to evaporate that water in the kiln. Over the past decades the US industry have made major efforts to shift to dry processes and almost 93% of the cement produced in the US is manufactured through dry processes (PCA, 2013). From the publication 'US and Canadian Labor-Energy Input Survey 2012' the cement industry in the US has improved energy efficient by more than 41% since 1972 (PCA, 2013).

Four dry processes can be distinguished: long dry processes, dry with preheater, dry with preheater/precalciner and semi-dry process. The have improved thermal energy efficiency and productive capacity given that moisture content is kept minimal in the raw material feed.

In **preheater dry processes**, through the addition of preheater vessels, the hot exhaust gases exiting the kiln pass counter-currently through the downward moving raw materials before they enter the rotary kiln. As a result, the rate of heat transfer is increased, the degree to which heat is utilized is increased and the process time in the kiln reduced (EPA, 2010).

The **preheater/precalciner** process showed additional increase in thermal energy efficiency and gain in productive capacity through the addition of a calciner vessel at the base of the preheater tower (the structure that supports the heater vessels). A significant amount of fuel is diverted from the kiln to the calciner, but at least 40% of fuel remains required for the rotary kiln. The amount of fuel diverted depends on the availability and source of the oxygen for combustion in the calciner (EPA, 2010).

In this paper, this process will be the one considered as standard when comparing the use of engineered fuels instead of fossil fuels in the cement production process. Figure 2 is a schematic of the entire cement production process with preheater/precalciner present.

(Source: DSMAC, 2014)
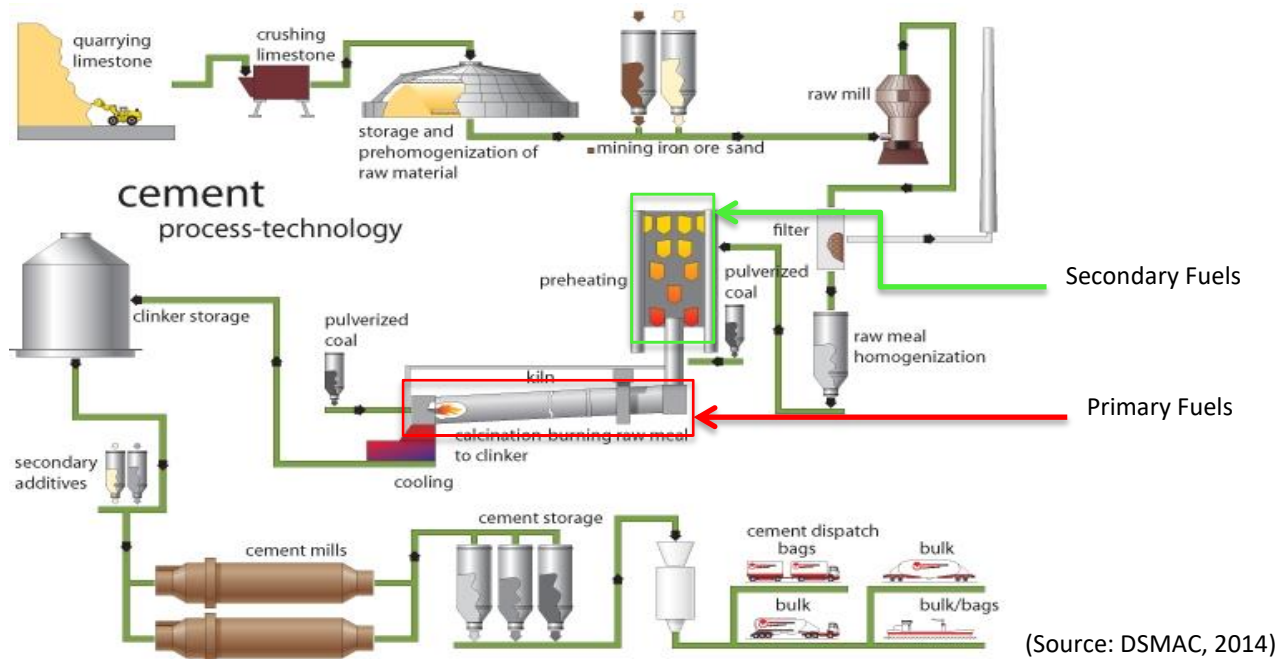
Figure 2: Schematic of a preheater/precalciner cement production process

The ***semi-dry process*** is a variation of the dry process: water is added to the dry raw mix to form moist pellets which are then conveyed on a moving grate preheater before being fed to the rotary kiln. The pellets are dried and partially calcined in the grate by hot kiln exhaust gases passing through the grate (EPA, 2010).

Regardless of the process type, the last part of the first step is the same: the clinker cooler. The clinker is fed to a cooler (reciprocating grate, planetary or rotary) where 30% of the heat input is recovered to the kiln system. Desirable products are locked in by freezing mineralogy; the clinker is cooled from about 1100 to 100 C by ambient air that passes through the clinker and to the rotary kiln (EPA, 2010).

The final product of this phase is called 'clinker'.

Step 2: cement production

Gypsum (calcium sulfates) or natural anhydrite (and sometimes other materials – cementitious like coal fly ash or inert like limestone) is added to the clinker. The constituents are ground to a fine homogenous powder in a grinding mill, which may be located in a different place than the

clinker plant. Cement is stored in silos, and the dispatched in bulk or bagged (Cement Bureau, 2014).

3.2.2   Fuels used and energy requirements

The amount of energy required to produce 1 ton of cement has been approximated at 4.982 million BTUs / ton of cement for US plants. The pyroprocessing step (preheater/precalciner followed by rotary kiln) accounts for 74.2% of this energy (Choate, 2003).
The Portland Cement Association reported an estimated 4.4 million BTU requirement per ton of cement produced (PCA, 2013). This is equivalent to 4642 MJ/ton cement produced.

On average, rotary kilns operate with a thermal energy efficiency of 34% (Choate, 2003). This relatively low number leaves a big opportunity to improve thermal performance. Over the past decades, the cement industry focused widely on types of fuels being used in the pyroprocessing. A major shift resulting from federal legislation from petroleum and natural gas based fuels to petroleum coke and coal has take place (Choate, 2013). Consequently higher CO_2 emissions per BTU consumed resulted since coal combustion generates 1.8 times more CO_2 than natural gas and 1.2 times more than residual oil on a BTU basis.

Continuous changes have been occurring in order to:
1. Reduce the BTUs required/ ton of cement produced (energy efficiency)
2. Decrease the amount of pollutants, and mainly CO_2, generated for each ton of cement produced
3. Save the fossil fuel reserves of the planet

Alternative fuels were introduced and as a result not only did they contribute to achieving the goals mentioned above but also they reduced the amounts of waste that would have otherwise been landfilled. This combination of improvements
Along these lines benefits such as saving the fossil fuel reserves and safely disposing of waste that would otherwise be landfilled eventually gained importance as well.

Waste co-processing in cement plants:

Waste co-processing into alternative fuels and raw materials in cement plants is a method used worldwide to process and dispose of waste in a completely safe manner. Two main types of waste can be processed:

• Waste with high energetic content – energetically recovered as an alternative fuel;

• Waste with a mineralogical content similar to the traditional raw material or to the intermediate product (clinker) – materially recovered as alternative raw material.

Regardless of the type of waste, waste co-processing under controlled conditions (from the OH&S, environmental protection and quality point of views) has various benefits:

• Preservation of natural resources by the partial substitution of fossil fuels (coal, oil, gas) and raw materials (limestone, clay and marl) with alternative ones;

• Indirect reduction of gas emissions, which would result from other ways of waste processing (incineration, landfilling...);

• Reduction of cement production costs (mid to long-term) if and only if all the collection, transport, pre-treatment and co-incineration

Improving energy efficiency:

The cement production process requires huge amounts of electrical and thermal energy. Energy efficiency, defined as the total thermal energy consumed per ton of clinker produced and as the total electric energy consumed per ton of cement produced, is almost entirely determined by the technology applied in the production process.

The improvement of energy efficiency not only reduces production costs, but also positively contributes to the preservation of natural resources (fuels) and the lowering of greenhouse gas (CO_2) emissions generated by fuel combustion in the cement kilns, as well as by electric energy production in thermo power plants.

Energy efficiency is also developed by using alternative fuels: besides the fact that this method allows the disposal of various wastes in an ecological manner, significant decreases in the conventional fuels consumption are also obtained.

Table 1 summarizes the repartition of fuel use for cement manufacturing in the US in 2000 (Choate, 2013) and 2011 (Cement, 2011). The use of alternative fuel clearly increased from 9 to 12% with a major shift in contribution from tires to solids, which include the engineered fuel that is discussed in this paper.

Table 1: Fuel consumption in US cement kilns in 2000 and 2011

	2000		2011*	
	MJ/ton clinker	%	MJ/ton clinker	%
Conventional Fuels				
Coal	3,148	67%	3,438	68%
Pet Coke	803	17%	640	15%
Natural Gas	276	6%	414	5%
Middle Distillates	42	1%		
Residual Oils	4		26	0%
Gasoline	5			
LPG	0			
Alternative Fuels				
Oils	16	0%		
Solvents	266	6%		
Tires	122	3%	191	4%
Solids	13		233	8%
EF	8			
Fuels total	4,702	100%	4,943	100%

*HHV used to convert from quantity used to energy provided http://www.cementkilns.co.uk/data_waste.html

Because fuel used in the rotary kiln (known as primary fuel) can affect the composition of the final product, namely the clinker, the composition of the fuel itself is of high importance in the cement production process. This primary fuel makes up no more than 45% of the total fuel used to feed the kiln and preheater/precalciner. The secondary fuel, which is the one fed to the preheater/precalciner in dry processes can be flexible in composition and calorific content given

that it does not affect the quality of the clinker product. It contributes to up to 55% of the total energy requirements of the process and therefore presents a major opportunity for energy efficiency improvement (see Figure 2).

The total calorific amount reported by industry in Table 1 that is provided by fuels to the cement production process is very compatible with the theoretical value of ±4600 MJ/ton found in literature (and mentioned in the beginning of this section).

3.2.3   Emissions

3.2.3.1 Emissions from the production process

The main emissions in cement production plants are: Particulate Matter (PM), nitrogen oxides (NO_x), sulfur dioxide (SO_2), carbon monoxide (CO) and carbon dioxide (CO2). Other emissions of concern may include Volatile Organic Compounds (VOCs), hydrogen chloride (HCl), ammonia (NH_3) and chlorine. Emissions may also include residual materials from the feed or raw materials as well as hazardous products of incomplete combustion (EPA, 2010).

The largest emission source of PM is the kiln and clinker cooler exhaust stacks. Emissions from Portland cement plants are regulated to limit PM emissions from cement kilns 0.15kg/ton of feed (dry basis) and to limit PM emissions from clinker coolers to 0.05 kg/ton of feed (dry basis) (EPA, 2010).

Nitrous oxides are generated through two paths. One hand oxidation of chemically bound nitrogen in the fuel occurs; and the more nitrogen-rich the fuel, the more NO_x emitted. On the other hand, thermal fixation of nitrogen in the combustion air takes place; the higher the temperature of the flame, the more thermally generated NO_x emitted. The type of fuel used and the temperature of the vessel therefore affect NO_x emissions. In the preheater/precalciner dry process, NO_x is produced in both the burning zone of the kiln and the burning zone of the calciner. For example, in the kiln, low nitrogen fuel such as natural gas combustion with high flame temperatures results in a larger generation of NO_x, compared to combustion of oil or coal which are high nitrogen fuels but burn at lower temperatures. The opposite may be true in the precalciner. Different plants use different combinations of fuels, but in recent year the trend of mixing coal and waste fuel has been

remarkable (EPA, 2010). The effect of waste fuel use on NO_x emissions s not clearly established but one may hypothesize that because of the variability of waste across regions and seasons as well as the numerous sources of waste, nitrogen content in the waste fuel would be highly variable and therefore emissions not necessarily predictable.

Sulfur dioxide may be generated from the sulfur content of the raw materials and the one in the fuel. Sulfur content of fuel and raw materials vary with each plant and geographic location. However, the alkaline nature of cement allows absorption of SO2 into the product, hence reducing the net emissions in the exhaust streams. Absorption ranges from 70 to more than 95% depending on process type and source of sulfur (EPA, 2010).

Carbon dioxide emissions result from two mechanisms: fuel combustion and calcination of limestone and other calcareous materials. Calcination refers to the thermal decomposition of limestone ($CaCO_3$) into calcium oxide (CaO) and CO_2. Typically cement contains 63.5% of CaO. A basic material balance shows that each ton of cement produced generates 0.500 tons of CO_2 (EPA, 2010). Another report stated 0.544 tons of CO_2/ton of cement (Choate, 2003). Adopting a rough estimate of 0.5 ton CO_2/ton cement seems realistic.

Depending on fuel type, burner choice, burner controls, kiln operation and heat recovery equipment (Choate, 2003). The total CO_2 emissions, including fuel-based CO_2 generation, are in the range from 0.85 to 1.35 tons of CO_2 per tons of clinker (EPA, 2010).
As a result of non-complete combustion, other pollutant like VOCs and CO can be emitted in smaller quantities. High temperatures and long residence time in the kiln provide little opportunity for CO emissions to occurs in general (Choate, 2013). Specific hazardous pollutants can be emitted sometimes, at even lower levels.
Metallic emissions can be grouped in three categories:
1. Volatile: mercury (Hg) and thallium (Tl);
2. Semi volatile: antimony (Sb), cadmium (Cd), lead (Pb), selenium (Se), zinc (Zn), potassium (K) and sodium (Na);
3. Refractory or non-volatile: barium (Ba), chromium (Cr), arsenic (As), nickel (Ni), vanadium (V), manganese (Mn), copper (Cu) and silver (Ag) (EPA, 2010).

3.2.3.2 Standard emission requirements in the US

The EPA reported the updated the 'National Emission Standards for Hazardous Air Pollutants for the Portland Cement Manufacturing Industry and Standards of Performance for Portland Cement Plants' in February 2013; Table 2 summarizes these numbers.

Table 2: National emission requirements for air pollutants from cement kilns

Pollutant	Cement kilns burning traditional fuels*	Cement kilns burning non hazardous waste*	
		Source units	g/ton ckr
Mercury	21 lb/ MM tons of feed	0.0037 mg/dscm	0.00851
THC	24 ppmv	24 ppmv	39.1
PM	0.02 lb/ton clinker	2.2 mg/dscm	5.06
HCl	3 ppmv	3 ppmv	10.2902
SO_2	0.4 lb/ton ckr	28 ppmv	181.7
NO_X	1.50 lb/ton ckr	200 ppmv	931.5
CO		90 ppmv (long kilns) 190 ppmv (preheater/precalciner)	538.2
Pb		0.014 mg/dscm	0.0322
Cd		0.0014 mg/dscm	0.00322
Dioxins, Furans, Total		0.51 ng/dscm	0.001173
Dioxins Furans, TEQ	0.2 ngTEQ/dscm	0.075 ng TEQ/dscm	0.0001725

∗ sources: EPA/UNEP, 2013 and Federal Register 2013

4 ENGINEERED FUEL: A PARTIAL SUBSTITUTE FOR CONVENTIONAL FUELS IN CEMENT KILNS

4.1 Motivation behind reusing residue

4.1.1 Economical and environmental drawbacks of landfilling in the US

In 2012, 135 million tons of MSW ended up in landfills. This amount represents 53.8% of the total MSW generated in the US that year, according to the values reported by the EPA. A study conducted by Dolly Shin at the Earth Engineering Center at Columbia University proved that the numbers reported by the EPA regarding MSW generation are smaller than the actual figures reported in a survey done by Shin over the 51 states for the year 2011. Based on her results, the total MSW generation amounted to 389 million tons in 2011 instead of the reported value of 250.4 million tons. The actual amount of waste sent to landfills that year was 247 million tons, corresponding to i.e. 63.5% of MSW generation (Shin, 2014), instead of 134 million tons claimed by the EPA (i.e. 53.6% of the total figure reported by the EPA). The fact that landfilling has been the cheapest waste management solution available justifies this high percentage. However, with increasing waste generation, more landfills are reaching their maximal capacity making the cost of landfilling gradually increase. Not to mention the additional fees associated with transporting the waste to landfills away from the cities, where capacity has been reached like in New York City for example. Landfilling is becoming a more expensive waste management practice (Tsiamis, 2013). According to Figure 3, the amount of waste landfilled since 2000 has been decreasing, but at a very low rate with respected the increasing amount of total waste generated at the same time (EPA, 2012).
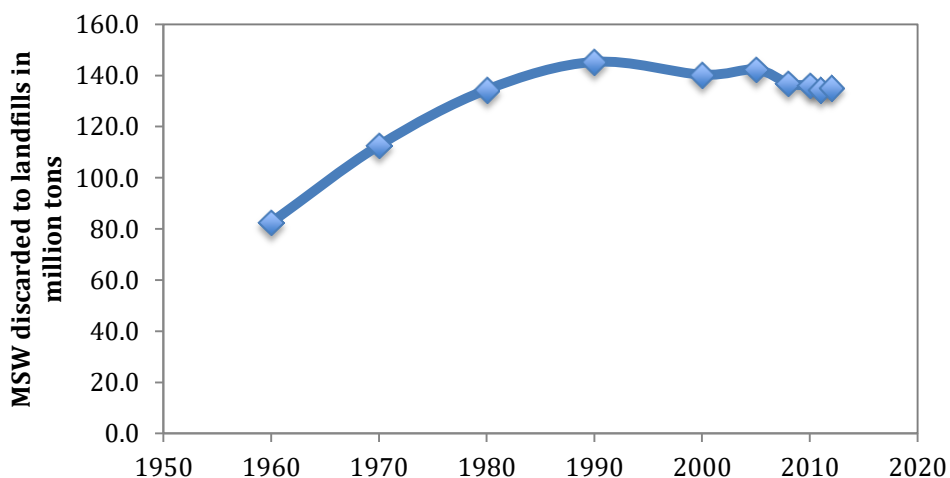
Figure 3: Mass of MSW discarded to landfills in the US since 1950

Direct consequences of landfills include without being limited to polluting the environment, reducing green spaces and bothering the surrounding communities aesthetically or even by threatening their health with disease-causing pathogens if operated improperly. Landfilling is definitely the least sustainable waste management practice and diversion methods are of major importance.

The waste in landfills should be seen as a source of energy and material recovery and therefore a large opportunity for alternative waste management practices such as waste to energy and recycling.

4.1.2   Waste management hierarchy

The waste management hierarchy ranks different waste management practices according to their environmental impacts. Because landfilling is not a sustainable practice and has the most negative impacts relative to all other available solutions, it is ranked as the worst practice. Figure 4 shows the waste management hierarchy suggested by the Earth Engineering Center at Columbia University.

Figure 4: Updated waste management hierarchy in the US (Source: Themelis, 2008)

It is clear that waste reduction is the most feasible solution economically and environmentally. Since that doesn't seem to be happening currently, the preferred practices include recycling and

composting of source-separated organic materials. Waste-to-energy refers to all processes that involve complete combustion of waste as a source of energy for different purposes such as electricity generation, cement production and other applications. In 2012, the EPA reported that 11.7% of the total MSW generated in the US was used in Waste-to-Energy applications (EPA, 2012).

4.2   Two case studies

The entire CEMEX company counts 61 plants spread over the US and Mexico and ranks 7th according to globalcement.com in both the top 20 and top 75 cement companies lists from 2011 (Global Cement, 2011). The results are calculated from clinker capacity assuming 95% clinker factor.

4.2.1   Data from Plants (Tepeaca plant)

4.2.1.1   Who is Tepeaca?

The Tepeaca plant is located in the area of Puebla in Mexico and produces 3.30 million tons of cement per year. Data on fuel consumption, cement and clinker production as well as emissions were provided for both years 2012 and 2013. Values were reported on a monthly basis for both fuel consumption and cement/clinker generation but on an annual basis for emissions.

4.2.1.2 Fuel data

4.2.1.2.1 Types of fuels used

The Tepeaca data that was received states the use of seven different fuels in the cement production process. It is not mentioned which ones are used as primary fuels (in the kiln) and which ones serve as secondary fuels (in the preheater/precalciner). If some fuels are used in both steps, the ratios are not given either. Also, from literature review, it is found that the incorporation of engineered fuels can be done only in the secondary fuel stream. A clarification on this point would be useful to know whether the data collected represents total fuels used, or just secondary fuels.

The seven fuels that are being used, and units in which raw data was reported, in the Tepeaca plant are the following:

1. Combustibles (m^3)
2. Petroleum coke (tons)
3. Gas
4. Oils
5. Litter coke
6. Biomass (tons): this fuel includes
7. Liquids
8. Whole tires (tons)
9. Tires
10. Engineered fuel (tons)
11. Residual carbon (tons)
12. Solids (tons)
13. CX004
14. MASA

From the data provided, gas, oils, litter coke, liquids, tires, CX004 and MASA can be discarded since they have not been used in any month of both years 2012 and 2013. This leaves seven fuel types to be considered. Figures 5 and 6 represent the amounts of different fuels fed to the cement kiln on a monthly basis for the years 2012 and 2013 respectively.

Notice the different units used to report the data depending on fuel type. Therefore all discussion referring to these figures will look at each fuel type separately. A direct comparison between different types is not sound unless the density of combustibles is determined hence transforming the data from volume to mass.

Monthly fuel use by type in 2012
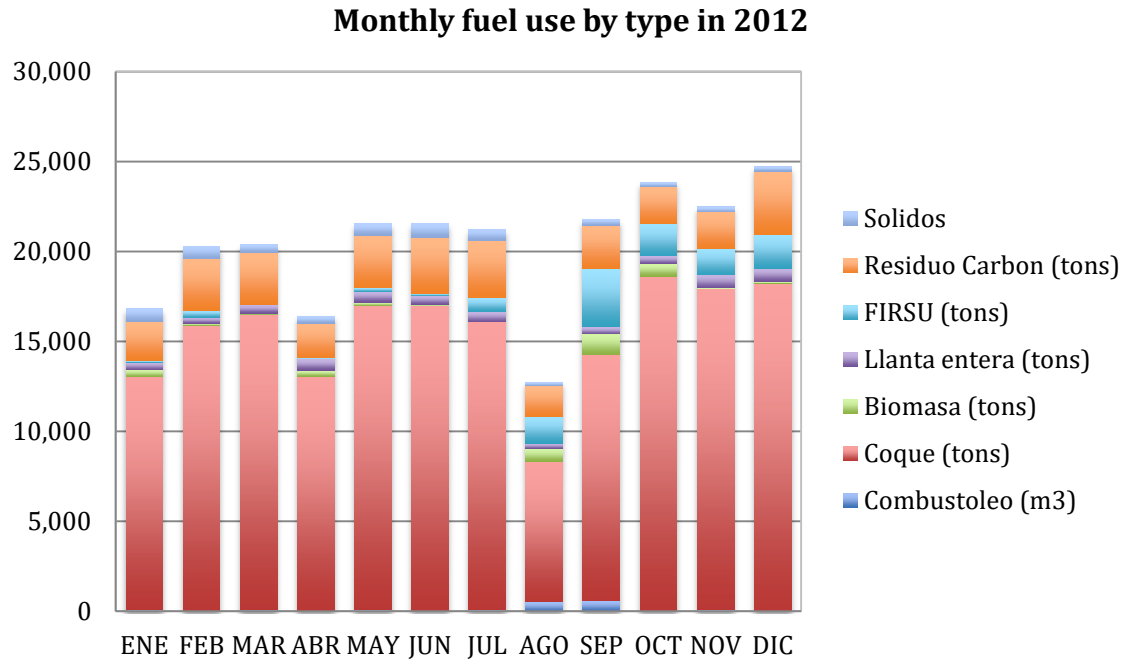
Figure 5: Monthly fuel use in Tepeaca, by type, in 2012

Monthly fuel use by type in 2013
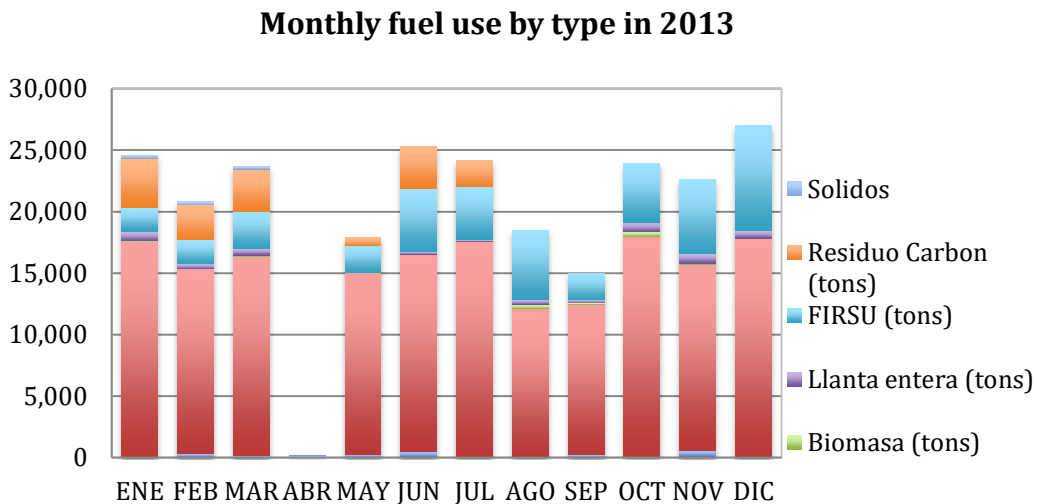
Figure 6: Monthly fuel use in Tepeaca, by type, in 2013

It is obvious from Figures 5 and 6 that even without knowing the density of combustibles, the biggest contribution of fuel to the cement kiln is made by pet coke, a 100% fossil fuel. The second fuel by quantity was the group of residual carbon materials in 2012 compared to engineered fuel in 2013. This observation is an indication that engineered fuel partially substituted fossil fuels since quantities of both pet coke and residual carbon decreased making space for engineered fuels.

Figure 7 illustrates the relative amounts of different fuels used in both years.
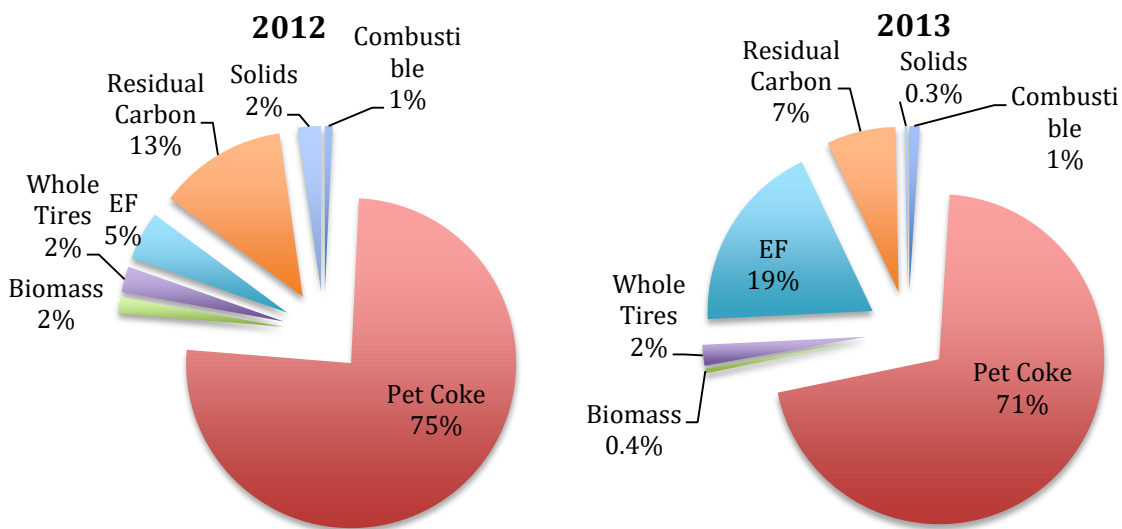
Figure 7: Relative amounts of different fuel used in Tepeaca in 2012 and 2013

Assuming that one metric is the quantity of fuel as a whole, the sum of all fuel amounts is 0.17% lower in 2013. Overall, it is safe to assume that the total amount of fuel used is the same. From Figure 7, it is seen that less pet coke was fed to the cement kiln in 2013. However, it is evident that the use of engineered fuel in 2013 increased significantly. There is an approximate 75% increase. This is a pertinent indicator that the substitution with engineered fuel was advantageous in the previous year. Concerning other types of fuel, smaller amounts were used in 2013 except for combustibles, which increased by approximately 33%.

Another way of looking at fuel consumption that is relevant to this paper is conventional fossil vs. non-fossil fuels. The grouping would be as follows:

Conventional Fossil fuels: Combustibles and Residual Carbon

Alternative Fuels: biomass, tires, solids and EF

Figure 8 shows that a 10% decrease in conventional fossil fuels usage was paralleled by a 14% increase in the use of engineered fuels, between 2012 and 2013. This shows two main changes: first, 10% of the fossil fuels were replaced by engineered fuels and second, engineered fuels were also successful in replacing other alternative fuels namely tires and solids which were less available in 2013.
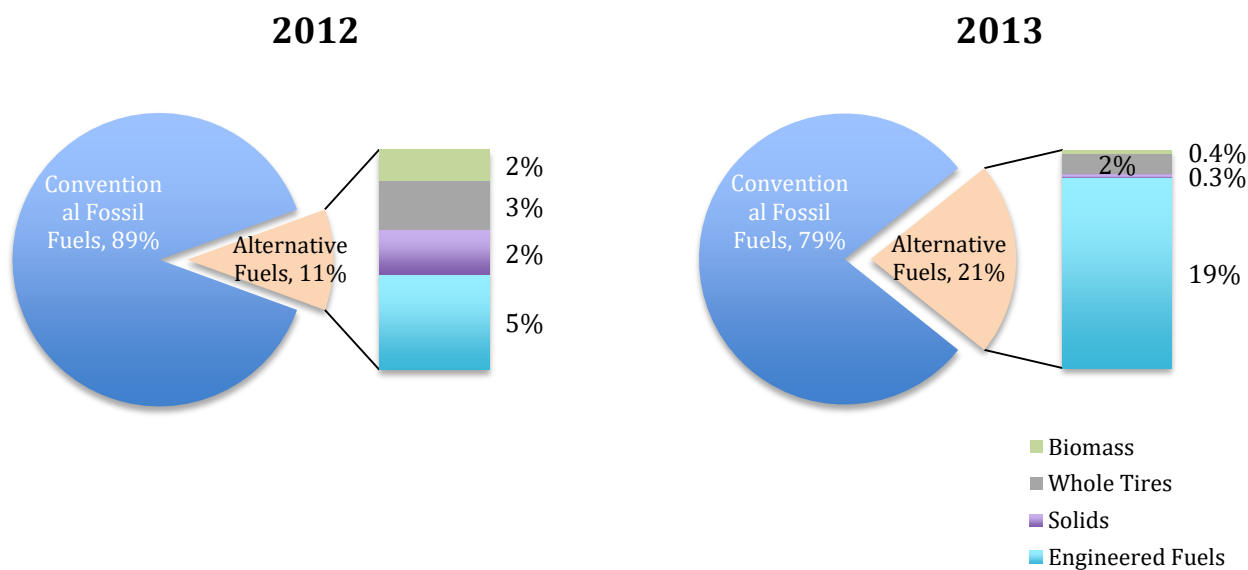
Figure 8: Conventional vs. alternative fuels used in Tepeaca in 2012 and 2013

An increase of 14% in one year and in just one plant is a very significant improvement that reflects the potential of substitution of fossil fuels by engineered fuels. The heating value of fuels is one of the main criteria that characterize the fuel, and its relevance to the process.

4.2.1.2.2   HHV of different fuels

The main characteristic of fuel in the cement production process is its heating value: how much energy it provides when combusted under atmospheric pressure and high temperatures observed in the kiln.

Based on the data provided by the Tepeaca plant, a weighted average heating value for each type of fuel used in 2012 and 2013 has been determined; the resulting values are shown in Figure 9.

Wt. average HHV (MJ.kg)

Combustible	39.00
Coke	34.09
Whole Tires	30.12
Solids	21.57
Residual Carbon	17.26
EF	15.09
Biomass	13.77
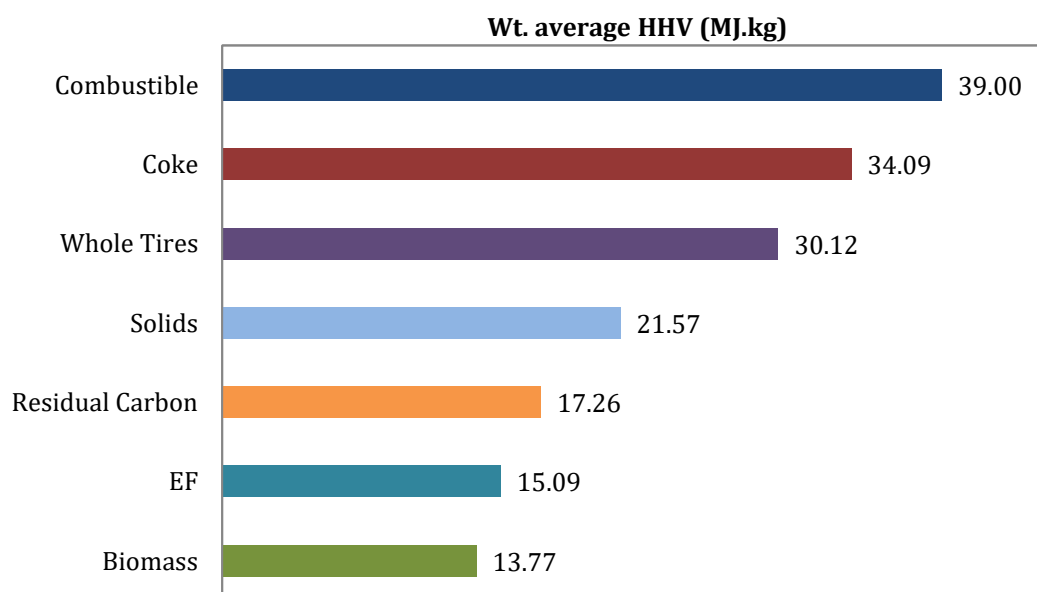
Figure 9: Weighted average of HHV of EF used in Tepeaca in 2012 and 2013

The range of heating values is relatively broad with biomass having the lowest HHV of 13.8 MJ/kg and combustible fuels the highest HHV of 39 MJ/kg. Engineered fuel falls 6th out of 7 fuels with an average value of 15.1 MJ/kg.

Mr. Enrique from CEMEX Tepeaca reported values for heating values in 2014 that are quite higher than those reported for 2012 and 2013. The average value reported for EF in 2014 is 17.5 MJ/kg. Variability of waste seems to be one of the biggest issues with respect to establishing a consistent energy content for the waste in order to proceed with other recommendations.

Interestingly, the relation between HHV of a certain type of fuel and the fraction it represents in the feed is not what one expects it to be. From figures 6 and 8, it is seen that pet coke, which is by far the most used fuel, has the second highest HHV of 34 MJ/kg, and that relation seems to be straightforward. However, the second most used fuel in 2013 was engineered fuel (19%) although it has one of the lowest HHV.

This observation is meaningful and promising with respect to the aim of this paper being to prove the efficiency of using more EF instead of fossil fuels in the process.

It is noteworthy that generally, in US based cement production plants, the main type of fuel used is coal, which has a relatively lower HHV than pet coke. Coal is found in different grades depending on its energy content which can be as high as 36 MJ/kg for bituminous coal and as low as 9 MJ/kg for lignite coal (American Coal Foundation, 2005). The most common type of coal used in the US for fueling industrial processes that involve burning the coal is subbituminous coal for its lower sulfur content (which makes it a cleaner burning fuel). Its energy content ranges from 19 to 30 MJ/kg (American Coal Foundation, 2005). By extrapolating to the US cement industry, EF and coal are therefore comparable with respect to heating content, if the EF used across the country is assumed to be similar in composition to the one used in Tepeaca.

Table 3 shows the HHVs determined from plant data versus those reported in literature (Zhang, 2013). The third column represents the difference as a percentage.

Table 3: Comparison of HHV of EF derived from plant data vs. literature findings			
Fuel type	**Plant data HHV (MJ/kg)**	**Literature HHV (MJ/kg)**	**Difference in %**
Combustible	39.00		
Coke	34.09		
Whole Tires	30.12		
Solids	21.57		
Residual Carbon	17.26		
EF	15.09		
Biomass	13.77		

4.2.1.2.3   Energy provided by each fuel

The total energy in mega joules (MJ) provided by each fuel type and the difference between 2012 and 2013 are shown in Table 4. Similarly, the total amount of fuels used and the difference between both years are shown in Table 5.

Table 4: Energy in MJ provided by each of type of fuel in Tepeaca in 2012 and 2013

Fuel type	MJ provided 2012	MJ provided 2013	% Change
Combustibles	72,228,886	96,105,338	33%
Pet Coke	6,367,658,655	5,783,889,836	-9%
Biomass	54,117,341	14,017,400	-74%
Whole Tires	188,761,866	144,902,489	-23%
EF	199,526,719	662,735,169	232%
Residual Carbon	539,854,841	274,593,451	-49%
Solids	121,821,389	13,359,717	-89%
Total	7,543,969,699	6,989,603,401	-7%

Table 5: Amount used by fuel type in Tepeaca in 2012 and 2013

Fuel type		Amount used 2012	Amount used 2013	% Change
Combustibles	(m³)	1,852	2,465	33%
Pet Coke	(tons)	184,239	172,258	-7%
Biomass	(tons)	3,872	1,078	-72%
Whole Tires	(tons)	6,140	4,937	-20%
EF	(tons)	11,595	45,548	293%
Residual Carbon	(tons)	30,693	16,483	-46%
Solids	(tons)	5,533	733	-87%

An important conclusion can be drawn from the tables 4 and 5. The changes in amount of fuel used and energy provided by each fuel type are the same with a margin of error of ± 3% at most for all fuels except EF. While the amount of EF used in the feed increased by 293%, the quantity of energy provided by EF increased by 232% only; this states that the heating value of EF is not as consistent as that of all other fuels. Variability of EF with respect to composition is one of the main limitations as to the extent to which cement plants can predict its energy content during different periods of time, and over different geographical areas.

Indeed, from Table 6, it is shown that the changes in HHV of other solid wastes and EF are close to 15% whereas the changes in HHV from 2012 to 2013 of all other fuels are at most 6.9% for tires and as low as -0.01% for combustibles.

Table 6: Difference in HHV calculated for fuels used in Tepeaca in 2012 and 2013

	HHV calculated (MJ/kg) 2012	HHV calculated (MJ/kg) 2013	% Change
Combustibles	39.00	38.99	-0.01%
Pet Coke	34.56	33.58	-2.85%
Biomass	13.98	13.01	-6.92%
Whole Tires	30.74	29.35	-4.54%
EF	17.21	14.55	-15.44%
Residual Carbon	17.59	16.66	-5.29%
Solids	22.02	18.23	-17.19%

4.2.1.3 Cement and clinker production

Table 7 shows the production quantities Tepeaca plant reported. With the use of more EF from 2012 to 2013, the production of clinker decreased by 9.6% and that of cement decreased by 3.3%. This decrease in production cannot be directly or strictly attributed to the change in fuel repartition. From Table 4, the total amount of energy in MJ provided by fuels in 2013 is 7% less than that provided in 2012 and that is the main explanation for decrease in production. A plausible hypothesis from the observation that a 7% decrease in fuel production was paralleled by only a 3% decrease in production is that productivity efficiency has increased as a result of shift towards more EF in the secondary fuel feed.

Table 7: Cement and clinker quantities produced in Tepeaca in 2012 and 2013

	Production 2012 (MMtons)	Production 2013 (MMtons)
Cement	2,941,033	2,848,153
Clinker	2,071,872	2,272,514

Table 8 summarizes the amount of fuel that was used per ton of cement and clinker produced in the Tepeaca plant in 2012 and 2013. Assuming that total energy requirement per ton of cement produced is a constant 4 MMBtu/ton of cement (as mentioned in Section 1.2.2), then the portion of fuel required in the pyroprocessing step turned out to be 60.8% of the total requirement in 2013 and 58.2% in 2013. These significantly lower percentages show that the Tepeaca plant has improved its thermal energy efficiency compared to the average US manufacturing plant on one hand, and from 2012 to 2013 on the other hand.

Table 8: Amount of fuel used per ton of product in Tepeaca in 2012 and 2013				
	2012		**2013**	
	MMBtu/ton produced	% of 4 MMBtu	MMBtu/ton produced	% of 4 MMBtu
Cement	2.43	60.8%	2.32	58.2%
Clinker	3.45	86.3%	2.92	72.9%

4.2.1.4 Emissions

Tepeaca plant reported their emissions for 2013 and 2013 as shown in Table 9.

Table 9: Emissions reported by Tepeaca for 2012 and 2013 compared to EPA standards					
		2012 g/ton clinker	**2013** g/ton clinker	**% Change**	**EPA std in** g/ton clinker
Particulate Matter	(PM)	8.46	3.78	-124%	9.08
Hydrochloric acid	(HCl)	12.66	29.196	57%	10.9202
Hydrogen fluoride	(HF)	NA	NA	-	-
Sulfur dioxide	(SO_2)	16.52	15.03	-10%	181.7
Nitrous oxides	(NO_x)	2079.40	496.09	-319%	931.5
Carbon monoxide	(CO)	533.38	655.76	19%	538.2
Cadmium & Thallium	(Cd+Tl)	0.00188*	See note		0.00322
Mercury	(Hg)	0.00018*	0.00002*	-816%	0.00851
Dioxins/furans		0.00389	0.00073	-434%	0.001173

*Data was below minimum detection level of lab equipment

**See Tables 2 and 3 , source EPA

*** EPA, 2014: http://www.epa.gov/osw/conserve/materials/tires/faq-tdf.htm#q5

Note:

- Emissions analysis are taken in a yearly basis by a certified, third party laboratory

- For 2012, Cd was 0.0000073 g/t clinker, while for 2013 it was 0.000046 g/t clinker; only 2013 was under minimum detection level

- g/t ckr = Units for institutional report to CSI

- NA = Not analyzed

- NO_x reported as NO_2, as required by institution

Although a thorough investigation on emissions data has still to be done, a first general look confirms that all emissions related to EF are below standard requirement for carbon dioxide, nitrous and sulfur oxides, particulate matter, heavy metals and dioxins. Dioxins quantities emitted

from the air pollution control unit of cement plants were reported to be independent of whether alternative fuels are used or not as fuel in the rotary kiln (EPA, 2014).

4.2.2 Experimental Testing (Balcones)

4.2.2.1 The Balcones cement plant of CEMEX

Based on published information from the CEMEX Balcones Cement Plant, the most updated data and facts state the plant has been operating since 1980 and earned the energy star - a program that was established by the EPA in 1992, to "conduct a basic engineering research and technology program to develop, evaluate, and demonstrate non–regulatory strategies and technologies for reducing air pollution – in November 2011. It underwent a massive expansion in 2008 after which its capacity of production of Portland cement reached 2.5 million tons of cement per year (Cemex, 2014).

4.2.2.2 Testing samples for fuel data

4.2.2.2.1 Experimental Setup Description

The Balcones plant sent the Earth Engineering Center a sample of each type of EF that they currently use as part of fuel feed to their rotary kiln. The plant did not report the ultimate analysis of the EF; neither did it specify the origin of the waste. The two types of sample received are shown in Figure 10: they will be referred to as fluff (left) and briquette (right) respectively.

Figure 10: Types of samples received from Balcones - Flull (left), Briquette (right)

The fluff and the briquette contain exactly the same waste material and have both been processed in the same way with an additional densifying step for the briquette at the very end of the processing. Its compact form makes the briquette easier to handle and to transport on the conveyor belts generally used to feed the fuel to the kiln, preheater and precalciner in cement production plants.

Using a Parr Oxygen Bomb Calorimeter, shown in Figure 12 (Sharobem, 2014), samples of < 0.8 grams were combusted with pure oxygen at 25 atmospheres. The protocol followed is ASTM D5468-02: "Standard Test Method for Gross Calorific and Ash Value of Waste Material". The procedure mainly covers all the required assumptions and error factors to be considered while determining the calorific value of Refuse-Derived Fuels using a bomb calorimeter. The parameters considered include but are not limitied to: sulfur and chlorine correction factors, fuse wire, radiation correction factor, etc. The sample is placed in a crucible where it is put in contact with a fuse wire. The bomb is securely closed, and filled with O_2 to 25 atm. In summary, the oxygen bomb is placed in a water bucket inside the jacket and closed. A 5-minute pre-stirring period allows the water temperature to homogenize before starting to record temperature readings. Temperature is recorded every minute until a stable temperature is observed. Following stable readings for approximately five minutes, the bomb's firing button is pressed and held for 5 seconds. The sends an electric current through the fues wire causing it to heat and ignite the EF sample, which initiates the combustion process of the entire sample.   This causes the temperature to rise quickly requiring temperature to be recorded every 15 seconds until a stable final temperature is achieved which is typically about ten minutes. Subsequently measurements are recorded every minute until the rate of change of temperature becomes null or constant over 5 consecutive 1-minute intervals. Table 10 and Figure 11 are included to show one of the data sets obtained in the table, and the curve representing the temperature rise during the test run in the figure.

Table 10: Sample Data Set for one Calorimetry Run

Time (minutes)	Temperature (°C)	Time (minutes)	Temperature (°C)
0	23.20	8 1/2	24.33
1	23.20	8 3/4	24.38
2	23.20	9	24.42
3	23.20	9 1/4	24.45

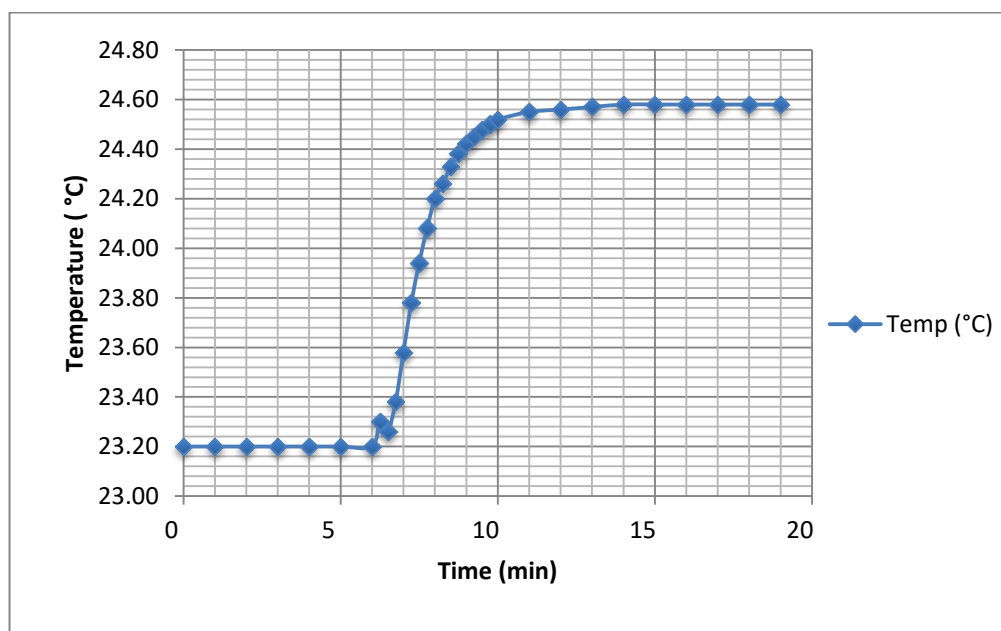| 4	23.20	9 1/2	24.48
5	23.20	9 3/4	24.50
6	23.20	10	24.52
6 1/4	23.30	11	24.55
6 1/2	23.26	12	24.56
6 3/4	23.38	13	24.57
7	23.58	14	24.58
7 1/4	23.78	15	24.58
7 1/2	23.94	16	24.58
7 3/4	24.08	17	24.58
8	24.20	18	24.58
8 1/4	24.26		

Figure 11: Temperature rise profile from 1 calorimetric run

Temperature rise is the main criterion to determine the HHV of the sample. For operational reasons of the calorimeter, a drop or two of water are added to the sample in the crucible, and

weighed. The HHV of the added moisture content is subtracted from the value calculated for the moist sample.

Figure 12: Experimental setup - Parr oxygen bomb calorimeter

4.2.2.2.2   Calibration

The calibration of the bomb calorimeter is important to determine the calorimeter constant, W, which represents the calories per degree Celsius absorbed by the instrument. A standard, benzoic acid in this case, is used for this calibration. By combusting benzoic acid pellets of known mass and heating value, H – the heat of combustion of the standard benzoic acid sample in calories per gram – is determined, and used in the computation of the heating value of the EF samples. W was found to be 2442.26 cal/°C.

4.2.2.2.3   HHV Computation

This section will elaborate on how the heating value of the samples received was determined. The different parameters that affect energy content are specified and quantified, and then processed according to the instruction manual of the Parr bomb calorimeter used to determine the heating value in MJ/kg of each EF sample tested.

For each sample tested, the following steps are completed to calculate an accurate HHV for the sample tested.

1. The temperature rise is determined using the following relation:

$$t = t_c - t_a - r_1(b - a) - r_2(c - b)$$

The parameters, which are defined shortly, are clearly represented in Figure 13.

- a, b and c are the time at which firing occurs (a), the time at which temperature is at 60% of the total rise (b) and the time of the beginning of the period at which the rate of temperature change becomes constant.
- t_a and t_c are the temperatures observed at both times a and c respectively.
- r_1 and r_2 are the rates of temperature change (units of temperature per time) observed during the 5-minute period before firing (r_1) and the 5-minute period after time c (r_2).

2. The correction factors are determined as follows:
a. Acid correction factor, e_1: by titration for HNO_3
b. Sulfur correction factor, e_2: by measuring sulfur content in the sample (weight %)
c. Fuse wire correction factor, e_3: by measuring length of non-consumed wire after test run

It was determined that both correction factors e_1 and e_2 are negligible compared to e_3 and to the actual HHV calculated. For example HHV = 17.25 MJ/kg and e1 and e2 where 2.5 and 11.70 calories respectively.

3. Using the constant value for H determined during calibration, the HHV of the moist sample is computed according to the following equation:

$$HHV_{moist}(cal/g) = \frac{tW - e_1 - e_2 - e_3}{m}$$

4. The heating value of the added moisture is subtracted from HHV$_{moist}$ and the net HHV is obtained.

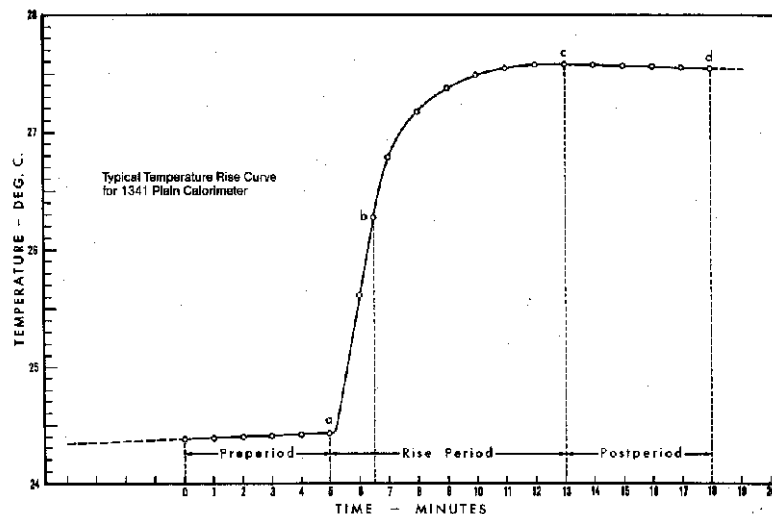Typical Temperature Rise Curve for 1341 Plain Calorimeter

Figure 13: Typical temperature rise curve and parameters used to calculate HHV

Table 11 reports the results obtained for 7 different fluff samples and 4 different briquette samples. Moreover, results concerning the biogenic vs. fossil carbon content of some of the samples are tabulated too. These will be further detailed and analyzed in the discussion of section 4.2.2.3.

Table 11: Results for HHVs of several runs on fluff and pellet EF from Balcones

	Fluff							Pellet			
	F-1	**F-2**	**F-3**	**F-4**	**F-5**	**F-6**	**F-7**	**P-1**	**P-2**	**P-3**	**P-4**
HHV (MJ/kg)	6.99	12.46	13.27	23.35	10.08	16.65	13.14	13.20	13.14	17.25	12.89
C14 analysis					19% F 81% B		29% F 71% B				40% F 60%B

By analyzing the standard deviation of each distribution of results, the HHV of fluff is **13.707 ± 2.597 MJ/kg** (equivalent to 5893.7 ±1116.7 Btu/lb) compared to an average HHV of **14.122 ±1.205 MJ/kg** (equivalent to 6072.1 ±518.2 Btu/lb).

Two points are noteworthy in this case: variability of the heating value within one category of fuel type, and magnitude of heating value of each type.

Variability

Variability is much more significant with fluff samples. One explanation could be that the heterogeneity of waste is not leveraged since waste is still scattered in the form of fluff; compared to a more consistent set of values obtained after running the test on different briquette samples.

Between the 7 fluff samples tested, variability ranged from 1% (F-3 and F-7) to 233% (F-1 and F-4). This range is very broad and two of the values obtained for F-1 and F-4 seem to be outliers among the 7 values.

Variability within the briquette samples tested ranges between 0.5% (P-1 and P-2) and 33.7% (P-3 and P-4). This suggests the variability in composition of waste and its heterogeneity.

If the outliers are ignored, then the fluff and briquette have similar heating values with an average of 13.02 MJ/kg.

Unpredictability of energy content of EF is therefore a major limitation regarding the extent to which it can substitute fossil fuels, which HHV is stable across regions and over different periods.

Magnitude

The difference between the average values for both types of engineered fuel does not lead to any unexpected conclusions, since additional tests are necessary to get a more accurate trend of values for the fluff samples that are being utilized. The range of 6 to 23 MJ/kg is large enough that more tests are required on an ongoing basis to check the likelihood of the heating values converging on a smaller range than measured here. The briquette form seems to have a more consistent and slightly (3%) higher HHV than the fluff.

Other factors

As mentioned previously sulfur content plays a negligible role in the correction of the heating value, since the differences obtained by assuming 0% sulfur content instead of the actual content, which ranged between 0.06 and 1.8% are less than 0.006%.

The average values obtained experimentally for fluff and pellet HHV (13.7 and 14.1 MJ/kg respectively) are both significantly different than the HHV mentioned by Zhang (17.8 MJ/kg), which was reported by the Balcones plant itself. It is noteworthy however, that the tests on F-6 and P-3 resulted in HHVs of 16.7 and 17.3 MJ/kg respectively, very comparable to Zhang's number. It is necessary to test many more samples, to be able to determine with certainty the specific heating value of the waste samples obtained from Balcones.

4.2.2.3 Emissions

4.2.2.3.1 Biogenic vs. fossil CO_2

Three gas samples resulting from combusting samples in the bomb calorimeter were collected in tedlar bags (Tedlar® 0.5-liter Sample Bag with single polypropylene septum fitting which combines the hose/valve and the septum holder into one compact fitting, pk/10 – SKC Catalog

Number: 232-02) and sent for analysis to Beta Analytic where biogenic versus non biogenic carbon content was analyzed.

'A standard has been developed to measure the biomass fraction of refuse-derived fuels and solid recovered fuels. This standard, EN 15440, determines the biogenic fraction of solid recovered fuels using radiocarbon dating techniques. EN 15440 is similar to the ASTM D6866 standard in the U.S. Both standards use the radiocarbon dating technique to distinguish the biogenic fractions of samples from their fossil-based components' (Beta Analytic, 2014).

Two gas samples contained combustion gases from runs done on fluff samples (namely F-5 and F-7, see table 1) and one sample had gases from calorimetric tests done on a briquette sample (namely P-4). The results are reported in Figure 14.
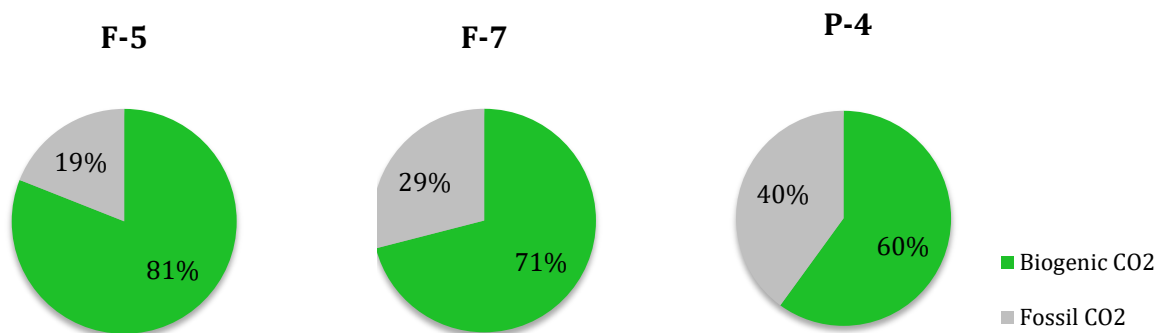
Figure 14: Biogenic carbon content of 3 sub-samples from Balcones reported through radiocarbon testing

The briquette sample has more fossil CO_2 than the fluff. The variability in content is significant between F-5 and F-7 and that can be attributed to variability of waste content. In general, the engineered fuel used, whether in the form of fluff or briquette contains less than 50% fossil CO_2 and that is an attractive property.

Compared to the other fuels used such as pet coke, which are totally fossil based, biomass has 100% biogenic CO_2, and tires should have no more than 30% biogenic CO2 (Beta Analytic, 2014). This said, engineered fuels contain the highest fraction of renewable carbon, and that is one of the advantages of using it to fuel the cement kiln.

The relation between carbon content and heating value is theoretically as follows: higher fossil carbon content means higher heating value, since fossil carbon is the core of plastics which have the highest heat content among all fuels. Tires, biomass, organic wastes, which are all made of biogenic carbon, have lower heating properties than conventional fuels. One interesting point would be to further understand the effect of biomass on heating value. Because biomass means higher oxygen content, the heating value of fuels containing more biomass does not vary; and therefore adding biomass to the alternative fuels used would not be attractive to cement producers. On the contrary, the amount of mole % of carbon decreases with added biomass because of the addition of oxygen entailed. Oxygen in fact does not add enthalpy as does carbon and hydrogen. From Figure 14, it is shown that the biogenic carbon content is higher in fluff than briquette versions of the same sample; therefore fluff is expected to have a higher heating value than briquettes. This was not the case in the experimental testing; however one should note that we did collect gas samples from each fuel sample burnt in the lab. This said, a clear and accurate conclusion regarding the correlation between heating value and nature of carbon content cannot be inferred given the partial number of gas samples sent for analysis. Each gas sample contains all the gases from the bomb at the end of the calorimetric test.

4.2.2.3.2   Other emissions reported

Table 12 summarizes the annual emissions reported by the Balcones plant for 2012 and 2013.

Table 12: Annual emissions reported by Balcones for 2012 and 2013

		2012 g/ton clinker	2013 g/son clinker	% Change	EPA standards**	EPA std in g/ton clinker
Particulate Matter	(PM)	NA	20.0180	-	0.02 lb/ton clinker	9.08
Hydrochloric acid	(HCl)	NA	NA	-	3 ppmvd	
Hydrogen fluoride	(HF)	NA	NA	-	-	-
Sulfur dioxide	(SO_2)	5.004	5.004	0%	0.5 ppmv	
Nitrous oxides	(NO_x)	1060.953	1000.899	6%	53 ppbv	
Carbon monoxide	(CO)	375.337	425.382	-13%	9 ppmv	
Cadmium	(Cd)	NA	0.00023521	-		
Lead	(Pb)	NA	0.00105094	-		

Mercury	(Hg)	NA	NA	-	21 lb/ MMton ckr	0.009534
Dioxins/furans			0.004 ng		0.4ng	0.4ng
		NA	TEQ/dscm	-	TEQ/dscm***	TEQ/dscm***

**See Tables 2 and 3 , source EPA

*** EPA, 2014: http://www.epa.gov/osw/conserve/materials/tires/faq-tdf.htm#q5

The high PM emissions are striking, since their amount is 2 times higher than standard requirements.

4.2.3   Comparing both plants

4.2.3.1   HHV

The average HHVs of EF used at the Balcones plalnt and obtained through calorimetric tests are similar to that reported by the Tepeaca Plant for 2012 and farther than the one for 2013; the values are shown in Figure 15.

The significantly higher HHV in Tepeaca in 2013 might be due to a change in the composition of the engineered fuel used. The similarity with the 2012 value might be a coincidence, or the fact that both plants used EF originating from the same source that year. More information is needed to interpret these observations. The HHVs were calculated, based on data reported by the Tepeaca Plant, as a weighted average of monthly amounts of EF used divided by the energy provided over the 12-month period for each year.
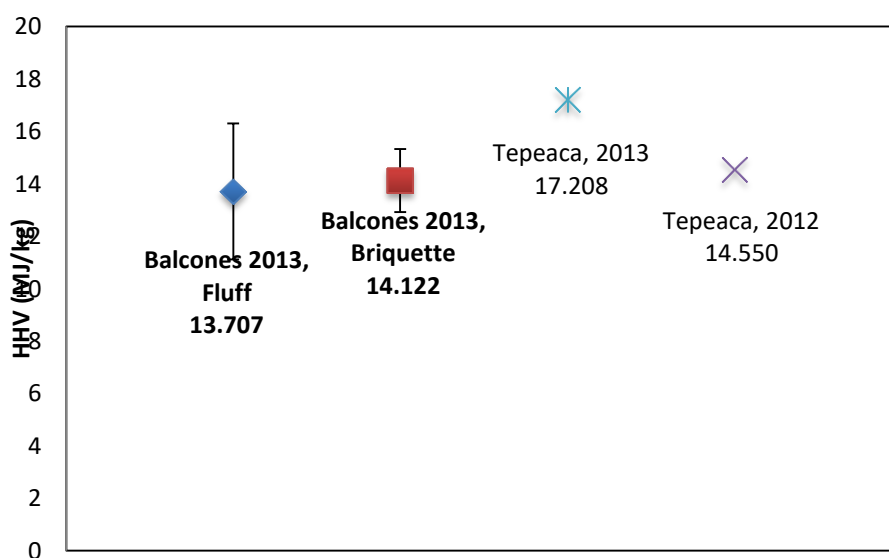

Figure 15: Average HHVs of fluff and pellet tested for Balcones vs HHVs of EF reported by Tepeaca

The physical form of EF used in Tepeaca is not specified, and therefore no comparison can be made regarding the effect of physical form to HHV.

Table 13 finally summarizes the heating values of the engineered fuels used in both plants.

Table 13: HHV in MJ/kg of EF used in both plants Balcones and Tepeaca

	Balcones	**Tepeaca**
Experimental testing CCNY	13. 7 and 14.1	-
Reported in 2012	-	14.6
Reported in 2013 by plant	17.8	17.2
Reported in 2014	-	17.5

4.2.3.2 Emissions

Emissions of both plants, for 2012 and 2013, are reported in the same units in Table 14. It is remarkable that emissions from Tepeaca are significantly higher than those from Balcones in 2012 for all components, and in 2013 for all except NOx emission which were decreased from 2079 to 496 g/ton ckr at Tepeaca compared to a decrease from 1060 to 1000 g/ton ckr in Balcones, putting Tepeaca as a lower emitter of NO_x for 2013.

Table 14: Comparison of emissions reported by Tepeaca and Balcones vs. standards

	2012*		**2013***		**EPA Stds***	
	Tepeaca	*Balcones*	*Tepeaca*	*Balcones*	*(std units)*	*(g/ton ckr)***
PM	8.46	NA	3.78	20.0180	9.08	9.08
HCl	12.66	NA	29.196	NA	3 ppmvd	
HF	NA	NA	NA	NA	-	
SO$_2$	16.52	5.004	15.03	5.004	0.5 ppmv	3.243
NO$_x$	2079.40	1060.953	496.09	1000.899	53 ppbv	246100
CO	533.38	375.337	655.76	425.382	9 ppmv	25.53

Cd+Tl	0.00188*	NA	See note	0.00023521		
Pb		NA		0.00105094		
Hg	0.00018*	NA	0.00002*	NA	0.009534	0.009534
Dioxins/Furans	0.00389	NA	0.00073	0.004 ng TEQ/dscm	0.4ng TEQ/dscm***	0.00092

* In g/ton ckr unless mentioned otherwise

** Assuming 2300 m³ exhaust gas are generated per ton of clinker produced, source:

http://www.wbcsdcement.org/pdf/CSI_TF4%20Emissions%20monitoring_Web.pdf

*** EPA, 2014: http://www.epa.gov/osw/conserve/materials/tires/faq-tdf.htm#q5

Note:

- Emissions analysis are taken in a yearly basis by a certified, third party laboratory

- For 2012, Cd was 0.0000073 g/t clinker, while for 2013 it was 0.000046 g/t clinker; only 2013 was under minimum detection level

- NA = Not analyzed

- NO_x reported as NO_2, as required by institution

The relative amounts of pollutants emitted are consistent with the quantities of cement produced where Tepeaca produces ±2.8 million tons of cement (Table 7) and Balcones manufactures a little less, around 2.5 million tons of cement (Cemex, 2014).

4.3 How did the use of EF evolve and how can it improve?

4.3.1 Current use of EF/RDF in cement kilns in the US

Because of opposition by some environmentalists, it takes a lot of time and effort to convince the public that waste is an actual fuel, even though its heating value may be lower than that of the conventional fossil fuels being used currently in processes such as cement production. The evolution is however taking place in the U.S., slowly but certainly. In the early eighties, when waste fuels started being introduced to cement kilns, they represented at most 3% of the total fuel composition fed to the kiln. By 2003, this percentage was up to 10.2% (EPA, 2008).
Table 15 (EPA, 2008) shows the different fuels used in the U.S. cement industry and their heating value. The similarity in heating content values reported by the Tepeaca plant of CEMEX for all fuel types and those obtained experimentally in this study for the engineered fuel (EF) used in the CEMEX Balcones plant is remarkable.

Table 15: Heating value of fuels used in the U.S. cement production
(EPA, 2008 – Sources: Cement Industry Contacts; Murray, A.E., and Price, L., 2008.)

Fuel type	Heating value (MJ/kg)	Notes
Coal	26.3	
Pet coke	34.0	
Paint residues	16.3	
Plastics	43.5	Polyethylene
	27.9	Mixed non-chlorinated
RDF	15.1 – 16.3	Post-processing
Scrap carpet	17.0 – 27.9	Nylon; Polypropylene
	27.9 – 34.9	Post-processing
Scrap tires	32.6	Tire derived fuel
Automobile shredder residue	16.3	Pre-processing
	23.3	Post-processing
Clarified slurry oil sediments	18.6 – 20.9	Centrifuged
Biosolids	16.3	Class A Dry
Paper/Cardboard	19.8 – 18.6	Dry
Sawdust	16.3	Dry
Wood	15.1 – 17.4	Dry
EF	23.3	[Processed Dry Kiln Fuel]
	15.1 – 18.6	Processed Wet Kiln Fuel]

At the end of March 2014, two updates concerning the fuels used by the cement industry in North America appeared in the news:

First an example of the changing trends in fossil fuel usage was the announcement by TruStar Energy of a deal to supply compressed gas to Argos USA (high-quality cement manufacturer, based in Houston). Another example of using alternative fuels in cement production was the announcement by the chemical waste firm ChemCare of its 100 million gallon milestone (379,000m^3) of fuel-quality waste supplied to the Lafarge co-processing subsidiary, Systech Environmental.

Jan Theulen of Heidelberg Cement pointed out another U.S. example during the Global CemFuels Conference held in Vienna in February 2014. He pointed out that rising landfill prices are increasing opportunities for alternative fuels, the same was true for the changing US Environmental Protection Agency (EPA) rules, now permitting for solid recovered fuel. Also, alternative fuels consultant Dirk Lechtenberg, in an interview with Global Cement Magazine in February 2014, singled out the US as one country that is developing its use of alternative fuels in cement production. As he explained, "Even though the fossil fuel prices are quite low in the US, the industry is developing supply chains for alternative fuels to be more independent with their fuels sourcing."

This race between cheaper fossil fuels in the US (e.g. shale gas) and increasing use of alternative fuels is fascinating. Specifically: why is it happening now? Gas prices have fallen and demand for cement is returning in the US. The annual mean Henry Hub natural gas spot price in the US fell from US$8.86/million Btu in 2008 to a low of US$2.75/million Btu in 2012. This compares with prices of up to US$15/million Btu in Japan and US$9/million Btu in Europe.

Public environmental pressure made manifest by the policies of the EPA and generally increased knowledge about the benefits of co-combustion may be factors for the surge in alternative fuels investment. Long lead times for alternative fuels schemes may be another. Planners who had to make a decision about what fuels mix to use in 2008, at the start of the recession, might well have bet on alternatives to spread their risk. Yet the cause could be something else, as shale gas takes over higher paying industries, such as electrical generation, and the cement industry continues to be priced out of the leftovers.

Ultimately what burns in a cement kiln comes down to price. Depending on how the shale gas market plays out in North America, it would be ironic if 'frackers', the bogeymen of current environmentalists, inadvertently helped the cement industry to use alternative fuels.

"We are committed to responsible waste management for our ChemCare customers, including the recycling of materials wherever possible. Our 25 year partnership with Systech has been an outstanding reflection of this, enabling the responsible disposal of waste while providing an alternative fuel source for cement kilns," said Greg Vas Nunes, vice president of ChemCare. Systech Environmental added that the arrangement had prevented the generation of 800,000t of CO_2. ChemCare provides waste management service that collects both hazardous and non-hazardous waste products at customer locations in the US and Canada. It then works with partners in the waste disposal business to transport these materials to licensed third-party treatment, storage and disposal facilities. Systech Environmental processes hazardous and non-hazardous industrial waste for use as fuel in cement kilns. It is actively processing or marketing fuels at 16 cement plants in the US.

4.3.2   A promising future for AF use in the global cement industry

To date, the main use of alternative fuels is in co-firing with conventional fuels in both cement kiln and power plants (coal and lignite power plants). Aside from government policy, there are two reasons why cement producers with access to low cost traditional fuels should consider alternative fuels: a) independence from fossil fuels and reduction of CO_2 emissions and b) securing waste sources as potential fuel sources for the future. Finding innovative ideas to allow existing cement kilns to receive larger amounts of alternative fuel, and to burn them as efficiently as fossil fuels would help municipalities deviate MSW significantly from landfills, and therefore improve the environmental situation of their communities.

5 CONCLUSIONS AND RECOMMENDATIONS

In conclusion, the use of alternative fuels in general, and engineered fuels in particular, is a promising innovation to the cement industry. Operationally, the heating value of engineered fuels examined in the case studies of this study (the two CEMEX plants in the U.S. and Mexico), along with figures found in the literature, of about 17 MJ/kg is lower than the 20-30 MJ/kg of coal or pet coke, respectively; however, both price and environmental emissions of NOx, SOx, and CO_2 are lower, as a result of burning less fossil fuels and more alternative fuels. Also, reduced landfilling is a second benefit that goes with the use of alternative fuels in cement kilns.
Economically, given that landfill gate fees are on a continuous increase, selling that waste to cement production facilities, even at a very low price, is a good way to reduce waste management costs of municipalities and benefit the environment at the same time.

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