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Use of Alternative Fuels in Cement Manufacture: Analysis of Fuel Characteristics and Feasibility for Use in the Chinese Cement Sector

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TABLE OF CONTENTS

TABLE OF FIGURES

TABLE OF TABLES

Abstract

Cement manufacturing is an energy-intensive process due to the high temperatures required in the kilns for clinkerization. The use of alternative fuels to replace conventional fuels, in particular coal, is a widespread practice and can contribute to improving the global warming impact and total environmental footprint of the cement industry. This report consists of three sections: an overview of cement manufacturing technologies, a detailed analysis of alternative fuel types and their combustion characteristics, and a preliminary feasibility assessment of using alternative fuels in China. This report provides an overview of the technical and qualitative characteristics of a wide range of alternative fuels including agricultural and non-agricultural biomass, chemical and hazardous wastes, petroleum-based wastes, and miscellaneous waste fuels. Each of these alternatives are described in detail, including a discussion of average substitution rates, energy and water content of the fuels, carbon dioxide emissions factors, and change in carbon emissions per ton of coal replacement. Utilization of alternative fuels in cement kilns is not without potential environmental impacts; emissions concerns and their effective management are discussed in general as well as for each alternative fuel type. Finally, the availability of a variety of alternative fuels is assessed in China along with the opportunities and technical challenges associated with using alternative fuels in China's cement manufacturing sector.

I. Introduction

Cement manufacturing is an energy-intensive process due to the high temperatures required in the kilns for clinkerization. In 2005, the global cement industry consumed about 9 exajoules (EJ) of fuels and electricity for cement production (IEA 2007). Worldwide, coal is the predominant fuel burned in cement kilns. Global energy- and process-related carbon dioxide (CO_2) emissions from cement manufacturing are estimated to be about 5% of global CO_2 emissions (Metz 2007).

Cement is made by combining clinker, a mixture of limestone and other raw materials that have been pyroprocessed in the cement kiln, with gypsum and other cementitious additives. Clinker production typically occurs in kilns heated to about 1450°C.

Globally, clinker is typically produced in rotary kilns. Rotary kilns can be either wet process or dry process kilns. Wet process rotary kilns are more energy-intensive and have been rapidly phased out over the past few decades in almost all industrialized countries except the US and the former Soviet Union. In comparison to vertical shaft kilns, rotary kilns consist of a longer and wider drum oriented horizontally and at a slight incline on bearings, with raw material entering at the higher end and traveling as the kiln rotates towards the lower end, where fuel is blown into the kiln. Dry process rotary kilns are more energy-efficient because they can be equipped with grate or suspension preheaters to heat the raw materials using kiln exhaust gases prior to their entry into the kiln. In addition, the most efficient dry process rotary kilns use precalciners to calcine the raw materials after they have passed through the preheater but before they enter the rotary kiln (WBCSD 2004). Table I-1shows the average fuel requirement of different kiln technologies in the US

Table I-1. Average energy requirement for clinker production in the US using different kiln technologies.

kiln type	clinker production (GJ/ton)
small wet plants (< 0.5 Mt/yr)	6.51
large wet plants	5.94
small dry plants (< 0.5 Mt/yr)	5.13
large dry plants	4.35
dry plants, no preheater	5.40
dry plants, preheater only	4.29
dry plants, precalciner	4.03

Adapted from : (van Oss 2002)

Vertical shaft kilns are still used in some parts of the world to produce cement, predominately in China where they are currently used to manufacture nearly half of the cement produced annually (Wang 2007). A shaft kiln essentially consists of a large drum set vertically with a packed mixture of raw material and fuel traveling down through it under gravity. Parallel evolution of shaft kiln technology with the more complex dry process rotary kilns kept the mix of pyroprocessing technologies in China's cement industry more diverse than in almost any other country.

Coal is the primary fuel burned in cement kilns, but petroleum coke, natural gas, and oil are also consumed. Waste fuels, such as hazardous wastes from industrial or commercial painting operations (spent solvents, paint solids), metal cleaning fluids (solvent based mixtures, metal working and machining lubricants, coolants, cutting fluids), electronic industry solvents, as well as tires, are often used as fuels in cement kilns as a replacement for more traditional fossil fuels (Gabbard 1990).

The use of alternative fuels to displace coal reduces reliance on fossil fuels, reduces emissions of carbon dioxide (CO_2) and other pollutants, and contributes to long-term cost savings for cement plants. Further, due to their high burning temperatures, cement kilns are well-suited for accepting and efficiently utilizing a wide range of wastes that can present a disposal challenge.

This report begins with an overview of the types of alternative fuels used in cement kilns, focusing on energy and environmental considerations. The types of fuels covered are agricultural biomass, non-agricultural biomass, chemical and hazardous waste, petroleum-based fuels, and miscellaneous alternative fuels. For each alternative fuel, information is provided on the potential substitution rate, energy content, emissions impacts, key technical challenges, and local considerations. The report then assesses the alternative fuel availability and feasibility of co-processing such fuels in cement kilns in China.

II. Use of Alternative Fuels

1. Introduction

Countries around the world are adopting the practice of using waste products and other alternatives to replace fossil fuels in cement manufacturing. Industrialized countries have over 20 years of successful experience (GTZ and Holcim 2006). The Netherlands and Switzerland, with respective national substitution rates of 83% and 48%, are world leaders in this practice (Cement Sustainability Initiative 2005). In the US, it is common for cement plants to derive 20-70% of their energy needs from alternative fuels (Portland Cement Association 2006). In the US, as of 2006, 16 cement plants were burning waste oil, 40 were burning scrap tires, and still others were burning solvents, non-recyclable plastics and other materials (Portland Cement Association 2006). Cement plants are often paid to accept alternative fuels; other times the fuels are acquired for free, or at a much lower cost than the energy equivalent in coal. Thus the lower cost of fuel can offset the cost of installing new equipment for handling the alternative fuels. Energy normally accounts for 30-40% of the operating costs of cement manufacturing; thus, any opportunity to save on these costs can provide a competitive edge over cement plants using traditional fuels (Mokrzycki and Uliasz- Bochenczyk 2003).

Whether to co-process alternative fuels in cement kilns can be evaluated upon environmental and economic criteria. As is discussed in detail below, the potential benefits of burning alternative fuels at cement plants are numerous. However, the contrary is possible, when poor planning results in projects where cement kilns have higher emissions, or where alternative fuels are not put to their highest value use. Five guiding principles outlined by the German development agency, GTZ, and Holcim Group Support Ltd., are intended to help avoid the latter scenarios (GTZ and Holcim 2006). The principles, reproduced in Table II-1, provide a comprehensive yet concise summary of the key considerations for co-incineration project planners and stakeholders. Similar principles were also developed by the World Business Council for Sustainable Development (Cement Sustainability Initiative 2005).

The following sections provide an overview of the technical and qualitative characteristics of a wide range of alternative fuels that can replace coal in cement kilns. These fuels include agricultural and non-agricultural biomass, chemical and hazardous wastes, petroleum-based wastes, and miscellaneous waste fuels. Each of these alternatives are described in detail, including a discussion of average substitution rates, energy and water content of the fuels, carbon dioxide emissions factors, and change in carbon emissions per ton[1] of coal replacement. (A combined table which also provides additional information – ash content, carbon content, and associated emissions – on of all of these alternative fuels is included in Appendix Table A.1). The information is presented as a comparative analysis of substituting different waste products for fossil fuel, addressing factors such as potential fossil fuel and emissions reductions, key technical challenges and local considerations. An understanding of the trade-offs among different fuel alternatives in the context of a particular cement operation will help to

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[1] This report defines ton according to the metric system (1 ton = 1000kg = 2,204.6 lb).

inform the decision-making process and lead to more successful coal substitution projects.

Table II-1. Guiding principles for co-processing alternative fuels in cement kilns

Principle	Description
co-processing respects the waste hierarchy	-waste should be used in cement kilns if and only if there are not more ecologically and economically better ways of recovery -co-processing should be considered an integrated part of waste management -co-processing is in line with international environmental agreements, Basel and Stockholm Conventions
additional emissions and negative impacts on human health must be avoided	-negative effects of pollution on the environment and human health must be prevented or kept at a minimum -air emissions from cement kilns burning alternative fuels can not be statistically higher than those of cement kilns burning traditional fuels
the quality of the cement must remain unchanged	-the product (clinker, cement, concrete) must not be used as a sink for heavy metals -the product must not have any negative impacts on the environment (e.g., leaching) -the quality of the product must allow for end-of-life recovery
companies that co-process must be qualified	-have good environmental and safety compliance records -have personnel, processes, and systems in place committed to protecting the environment, health, and safety -assure compliance with all laws and regulations -be capable of controlling inputs to the production process -maintain good relations with public and other actors in local, national and international waste management schemes
implementation of co-processing must consider national circumstances	-country specific requirements must be reflected in regulations -stepwise implementation allows for build-up of necessary management and handling capacity -co-processing should be accompanied with other changes in waste management processes in the country

Source: adapted from GTZ and Holcim Group Support Ltd., 2006.

2. Energy and Emissions Considerations

Using alternative fuels in cement manufacturing is recognized for far-reaching environmental benefits (CEMBUREAU 1999). The embodied energy in alternative fuels that is harnessed by cement plants is the most direct benefit, as it replaces demand for fossil fuels like coal. The amount of coal or other fossil fuel demand that is displaced depends on the calorific value and water content of the alternative fuel in comparison to coal. Average volumes required to replace one ton of coal are shown in Figures II-2

through II-6. Figue A-1 combines all of the alternative fuels considered in this study and ranks them from requiring the least to greatest volume to replace one ton of coal. Additionally, the fuel substitutes often have lower carbon contents (on a mass basis) than fossil fuels. The cement industry is responsible for 5% of global CO_2 emissions, nearly 50% of which are due to the combustion of fossil fuels (IPCC 2007; Karstensen 2008). Therefore, another direct benefit of alternative fuel substitution is a reduction in CO_2 emissions from cement manufacturing.

In addition to the aforementioned direct benefits of using alternative fuels for cement manufacturing, there are numerous life-cycle benefits and avoided costs that are realized. Alternative fuels are essentially the waste products of other industrial or agricultural processes, and due to their sheer volume and potentially their toxicity, they pose a major solid waste management challenge in many countries. Thermal combustion of these materials is a way to both capture their embodied energy and significantly reduce their volumes; this can be done in dedicated waste-to-energy incinerators or at cement plants.

Figure II-1 illustrates the benefits of co-combustion of alternative fuels in a cement plant (4). A life-cycle comparison of using dedicated incinerators and cement kilns reveals that there are significant advantages to the latter (CEMBUREAU 1999). Burning waste fuels in cement kilns utilizes pre-existing kiln infrastructure and energy demand, and therefore avoids considerable energy, resource and economic costs (CEMBUREAU 1999). Also, unlike with dedicated waste incineration facilities, when alternative fuels are combusted in cement kilns, ash residues are incorporated into the clinker, so there are no end-products that require further management.
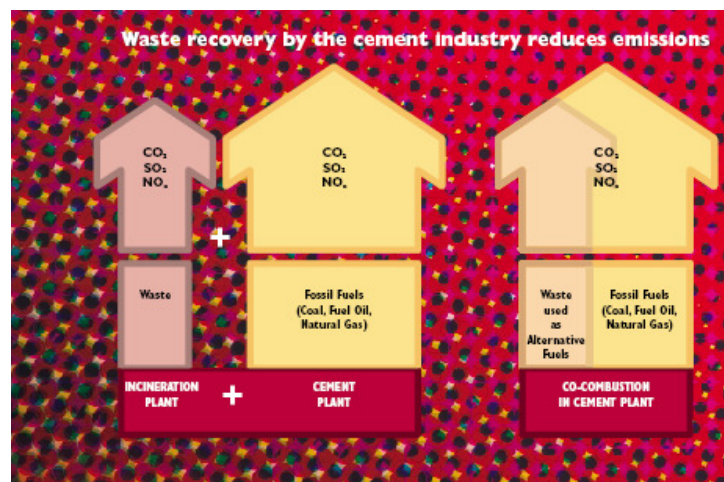
Figure II-1. Benefits of co-combustion of alternative fuels in a cement plant (4)

Through the acceptance and use of alternative fuels, cement manufacturers can play an important role in the sustainable energy and solid waste management strategies of many societies (CEMBUREAU 1997; Portland Cement Association 2006; Karstensen 2008). This is particularly true for countries with large cement manufacturing sectors, where the number of cement plants and their spatial distribution may facilitate the utilization of alternative fuels. However, it should be borne in mind that burning alternative fuels in

dedicated facilities or cement kilns is not without potential environmental impacts, such as harmful emissions, that need to be appropriately managed.

a. *Chlorine*

The presence of chlorine in alternative fuels (e.g., sewage sludge, municipal solid waste or incineration ash, chlorinated biomass,) has both direct and indirect implications on cement kiln emissions and performance. Methods have been developed to properly manage chlorine and its potential implications – but it is important that these implications be recognized and managed. Trace levels of chlorine in feed materials can lead to the formation of acidic gases such as hydrogen chloride (HCl) and hydrogen fluoride (HF) (WBCSD 2002). Chlorine compounds can also build-up on kiln surfaces and lead to corrosion (McIlveen-Wright 2007). Introduction of chlorine into the kiln may also increase the volatility of heavy metals (Reijnders 2007), and foster the formation of dioxins (see Dioxins and Furans discussion below.) If the chlorine content of the fuel approaches 0.3-0.5%, it is necessary for cement kilns to operate a bypass to extract part of the flue-gas thereby limiting the chloride concentrations in the clinker (Genon 2008). The gas bypass contributes an additional energy demand of 20-25 KJ/kg clinker (Genon 2008).

b. *Heavy Metals*

It has been demonstrated that most heavy metals that are in the fuels or raw materials used in cement kilns are effectively incorporated into the clinker, or contained by standard emissions control devices (WBCSD 2002; European Commission (EC) 2004; Vallet January 26, 2007). A study using the EPA's toxicity characteristic leaching procedure to test the mobility of heavy metals in clinker when exposed to acidic conditions found that only cadmium (Cd) could be detected in the environment, and at levels below regulatory standards (5 ppm) (Shih 2005). As long as cement kilns are designed to meet high technical standards, there has been shown to be little difference between the heavy metal emissions from plants burning strictly coal and those co-firing with alternative fuels (WBCSD 2002; European Commission (EC) 2004; Vallet January 26, 2007). Utilization of best available technologies is thus essential for controlling emissions.

Mercury (Hg) and cadmium (Cd) are exceptions to the normal ability to control heavy metal emissions. They are volatile, especially in the presence of chlorine, and partition more readily to the flue gas. In traditional incineration processes, Hg (and other heavy metals) emissions are effectively controlled with the combination of a wet scrubber followed by carbon injection and a fabric filter. Similar control options are under development for cement kilns including using adsorptive materials for Hg capture (Peltier 2003; Reijnders 2007). At present, the use of dust removal devices like electrostatic precipitators and fabric filters is common practice but they respectively capture only about 25% and 50% of potential Hg emissions (UNEP Chemicals 2005). The only way to effectively control the release of these volatile metals from cement kilns is to limit their concentrations in the raw materials and fuel (Mokrzycki, Uliasz-Bochenczyk et al. 2003; UNEP Chemicals 2005; Harrell March 4, 2008). Giant Cement, one of the pioneer hazardous waste recovery companies in the US, limits the Hg and Cd contents in alternative fuels for their kilns to less than 10 ppm and 440 ppm, respectively (Bech 2006). These limits are significantly lower than those for other metals such as lead (Pb),

chromium (Cr) and zinc (Zn) which can be as high as 2,900, 7,500, and 90,000 ppm, respectively (Bech 2006).

c. *Dioxins and Furans*

The formation of persistent organic pollutants such as polychlorinated dibenzo-*p*-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs), known collectively as dioxins, is a recognized concern for cement manufacturing. Dioxins have the potential to form if chlorine is present in the input fuel or raw materials. Formation can be repressed, however, by the high temperatures and long residence times that are standard in cement kilns (Karstensen 2008). Minimizing dioxin formation is further achieved by limiting the concentration of organics in the raw material mix, and by quickly cooling the exhaust gases in wet and long dry kilns (WBCSD 2002; Karstensen 2008). Evidence from several operating kilns suggests that preheater/precalciner kilns have slightly lower PCDD/PCDF emissions than wet kilns (Karstensen 2008).

The actual contribution of the cement sector to dioxin emissions remains controversial as the science of measuring these emissions is rather nascent (WBCSD 2002). For example, the EU Dioxin Inventory and the Australian Emissions Inventory measured dioxin emission factors that ranged by orders of magnitude (WBCSD 2002). In general, the US attributes a greater share of total dioxin emissions to the cement sector than do other countries such as Australia and those in the EU. The difference is largely due to divergent approaches to monitoring cement kiln emissions (WBCSD 2002).

With respect to alternative fuels, numerous studies comparing PCDD/PCDF formation in kilns using conventional and waste-derived fuels have found no significant difference in the emissions from the two (WBCSD 2002; WBCSD 2006; Karstensen 2008). They have also found that kilns using alternative fuels easily meet emissions standards (WBCSD 2002; WBCSD 2006; Karstensen 2008). For example, non-hazardous alternative fuels (used oil, tires, waste-derived fuels) fed into dry preheater kilns equipped with electrostatic precipitators in Germany found no significant difference in PCDD/PCDF emissions compared to traditional fuels (Karstensen 2008). Until recently, emissions factors for PCDD/PCDFs differentiated between plants that did and did not burn hazardous wastes. That distinction has been replaced with distinctions among kiln types and burning temperatures to determine appropriate dioxin emission factors (Table II-2).

Table II-2. Emissions factors for PCDD/PCDF emissions for kilns burning hazardous or non-hazardous waste as fuel substitutes based on kiln type, air pollution control devices (APCD) and temperature

	APCD > 300 °C	APCD 200 – 300 °C	APCD < 200 °C
shaft kiln	5 µg TEQ/ton		
dry kiln with preheater/precalciner	-	-	0.15 µg TEQ/ton
wet kiln	5 µg TEQ/ton	0.6 µg TEQ/ton	0.05 µg TEQ/ton

 Source: (UNEP Chemicals 2005)**.**

3. Agricultural Biomass Residues

Globally, agricultural biomass residues accounted for 0.25% of fuel substitutes used in cement manufacturing in 2001 (Cement Sustainability Initiative 2005). The use of agricultural biomass residues in cement manufacturing is less common in industrialized countries and appears to be concentrated in more rural developing regions such as India, Thailand, and Malaysia. The type of biomass utilized by cement plants is highly variable, and is based on the crops that are locally grown. For example rice husk, corn stover, hazelnut shells, coconut husks, coffee pods, and palm nut shells are among the many varieties of biomass currently being burned in cement kilns. Table II-3 provides a summary of the key characteristics of agricultural biomass as alternative fuels for cement manufacturing. Biomass is often used as a secondary fuel, thus is injected during secondary firing at the pre-heater.

Table II-3. Characteristics of agricultural biomass residues as alternative fuel

fuel	substitution rate (%)	energy content (LHV) (GJ/dry ton)	water content (%)	carbon emissions factor[b] (ton C/ton)	ΔCO_2[c] (ton/ton coal replaced)	data sources
rice husks	35	13.2; 16.2	10	0.35	-2.5	(Mansaray 1997; Jenkins, Baxter et al. 1998; Demirbas 2003)
wheat straw	20	15.8[a]; 18.2	7.3; 14.2	0.42	-2.5	(Jenkins, Baxter et al. 1998; Demirbas 2003; McIlveen-Wright 2007)
corn stover	20	9.2; 14.7; 15.4	9.4; 35	0.28	-2.5	(Demirbas 2003; Mani, Tabil et al. 2004; Asian Development Bank 2006)
sugarcane leaves	20	15.8[a]	<15	0.34	-2.5	(Jorapur 1997)
sugarcane bagasse	20	14.4; 19.4	10-15	0.39	-2.5	(Li 2001; Asian Development Bank 2006)
rapeseed stems	20	16.4	12.6	0.39	-2.5	
hazelnut shells	20	17.5[a]	9.2	0.48	-2.5	(Demirbas 2003)
palmnut shells	20	11.9[a]		0.36	-2.5	(Lafarge Malayan Cement Bhd 2005)

[a]Lower heating value (LHV) calculated based on reported higher heating value (HHV)
[b]Carbon emission factors calculated using method in Box I-1. IPCC default value for biomass is 0.03 ton C/GJ, the value was used for palmnut shells (IPCC 1996).
[c]Note: Change in CO_2 emissions assumes that biomass is carbon-neutral; negative values for change in CO_2 represent a net reduction in emissions.

a. Substitution Rate

As a rule of thumb, a 20% substitution rate of agricultural biomass residues for fossil fuel (on a thermal energy basis[2]) is quite feasible in cement kilns (Demirbas 2003). Biomass is highly variable which makes flame stability and temperature control in the kiln difficult when it is used in higher proportions. However, substitution rates of greater than 50% have been achieved but require boilers specifically designed for biomass handling (Demirbas 2003).

b. Energy Content

There is a wide range in the calorific values reported in the literature for agricultural biomass categorically, as well as for individual types. The range in lower heating values[3] (LHV) of agricultural biomass is from 9.2 – 19.4 GJ/dry ton; corn stover represents the low end and sugarcane bagasse the high end. For biomass varieties such as corn stover, rice husks, and wheat straw, that are the most widely available and used as alternative fuels, there is enormous range in their energy values reported in the literature. For example, for corn stover, Demirbas reports an equivalent LHV of 9.7 GJ/ton (Demirbas 2003), while Mani et al. report an equivalent LHV of 14.7 GJ/ton, and the Asian Development Bank reports an LHV of 15.4 GJ/ton (Mani, Tabil et al. 2004). The water contents of the various types of agricultural biomass also vary dramatically.

The quantity of agricultural biomass residues that are necessary to replace one ton of coal depends on the residue's energy value and water content. Based on the average values reported in Table II-3, and an assumed coal LHV of 26.3 GJ/ton, the range is between 1.6 and 2 tons of biomass residue per ton of coal replaced (Fig. II-2).

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[2] In other words, biomass can replace up to 20% of the total energy demand. Substitution rates on a mass basis are relative to the heat content of the alternative fuel in comparison to coal.

[3] The energy content of fuels can be reported in terms of the lower heating value (LHV) or the higher heating value (HHV), alternatively referred to as net and gross calorific value, respectively. The LHV assumes that the latent heat of vaporization of water in the material is not recovered, whereas the HHV includes the heat of condensation of water. This report provides the energy content of fuels in terms of LHV. When only the HHV was found in the literature, LHV was assumed to be 10% lower than the HHV, the conversion used by the International Energy Agency (IEA (2007). Energy Balances of Non-OECD Countries: Beyond 2020 Documentation, International Energy Agency**:** 77.). It is noted in Table II-3 if the LHV is an estimate.
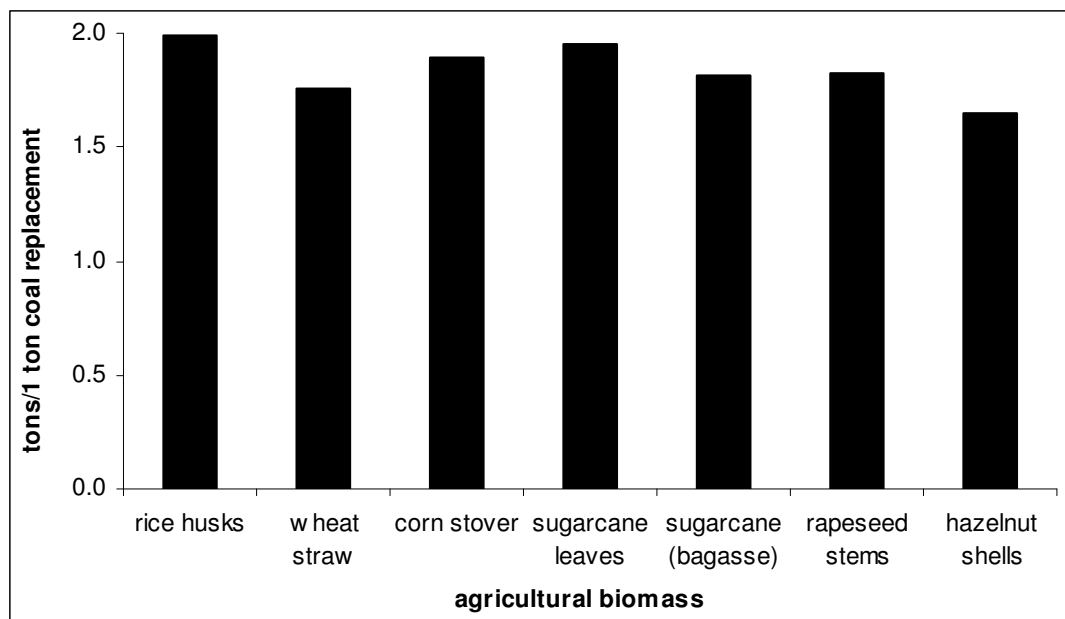
Figure II-2. Tons of agricultural biomass residues necessary to replace one ton of coal. Values are dependent on the material's energy value and water content. Calculations are based on average values reported in Table II-3 and a coal LHV of 26.3 GJ/ton.

c. *Emissions Impacts*

According to the Intergovernmental Panel on Climate Change (IPCC), biomass fuels are considered carbon neutral because the carbon released during combustion is taken out of the atmosphere by the species during the growth phase (IPCC 2006). Because the growth of biomass and its usage as fuel occurs on a very short time-scale, the entire cycle is said to have zero net impact on atmospheric carbon emissions. An important caveat to this assumption is that growing biomass and transporting it to the point of use requires inputs like fuel and fertilizer that contribute to the carbon footprint of biomass. When biomass is grown specifically for fuel, the upstream GHGs that are typically attributed to the biomass are those associated with fertilizer, collection, and transportation to the facility. When biomass residues are used, fertilizer is only considered part of the carbon footprint if residues that would normally stay in the fields to enrich the soil are collected. As an example of the magnitude of the CO_2 intensity of collecting and transporting biomass residues, according to the Biofuels Emissions and Cost Connection (BEACCON) model, corn stover has an associated cost of 94.8 kg CO_2/dry ton (Life Cycle Associates 2007).

Assuming carbon-neutrality, the emissions reductions associated with biomass residue substitution for conventional fuel are equivalent to the carbon emissions factor of the fuel that is replaced. On the basis of the assumptions used in this report for the carbon content of coal[4], biomass offsets 2.5 tons of CO_2 for every ton of coal that it replaces (Box I-1). The mass of biomass required to replace one ton of coal (or other fuel) is dependent on its LHV and water content in comparison to that of coal.

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[4]Assumes a carbon content of 68%; 0.68 tons carbon per ton coal.

Agricultural biomass has a highly variable calorific value and water content; thus the numbers reported in this document should serve for making general comparisons between different alternative fuel options. If a cement plant is seriously considering the use of a particular biomass residue for alternative fuel, the reported numbers are not a substitute for a cement plant's own analysis of the characteristics of the material in question.

In addition to serving as an offset for non-renewable fuel demand, the use of biomass residues has the added benefit of reducing a cement kiln's nitrogen oxide (NO_x) emissions. Empirical evidence suggests that the reductions in NO_x are due to the fact that most of the nitrogen (N) in biomass is released as ammonia (NH_3) which acts as a reducing agent with NO_x to form nitrogen (N_2) (McIlveen-Wright 2007). Interestingly, there does not seem to be a strong relationship between the N content in the biomass and the subsequent NO_x emissions reductions.(McIlveen-Wright 2007). There is currently no way to theoretically estimate the reductions, as the mechanism is not fully understand.

d.   *Key Technical Challenges*
All fuel types have unique combustion characteristics that cement plant operators must adapt to in order for successful kiln operation; biomass is no exception. The relatively low calorific value of biomass can cause flame instability but this is overcome with lower substitution rates, and the ability to adjust air flow and flame shape (Vaccaro and Vaccaro 2006). Biomass is prone to change with time, thus care must be taken to use the material before it begins to breakdown. Importantly, new biomass should be rotated into the bottom of storage facilities such that the oldest material is injected into the kiln first. Related to biomass conveyance, the flow behavior of different materials is quite variable, therefore, cement kiln operators must choose the method for injecting fuel into the kiln that will facilitate a constant and appropriate heat value.
The presence of halogens (e.g., chlorine) found in biomass such as wheat straw and rice husks may be a concern for slagging and corrosion in the kiln; however studies have shown that co-firing biomass with sulphur containing fuels (such as coal) prevents the formation of alkaline and chlorine compounds on the furnaces (Demirbas 2003; McIlveen-Wright 2007). However, ash deposits may decrease heat transfer in the kiln.

Box I-1. Method for calculating change in CO_2 with alternative fuel substitution

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Carbon neutral fuels (e.g., biomass)

The change in CO_2 per ton of coal replaced is equal to the CO_2 emissions factor for coal.

   Assumptions

Coal carbon emissions factor = 0.68 ton C/ton coal

   Calculation

Conversion of C to CO_2 :

$$\frac{0.68 \; ton \; C}{ton \; coal} \times \frac{44 \; ton \; CO_2}{12 \; ton \; C} = \frac{2.5 \; ton \; CO_2}{ton \; coal}$$

Non-carbon neutral fuels

The change in CO_2 per ton of coal replaced is the difference between the CO_2 emissions associated with the alternative fuel and with coal.

   Assumptions (example using spent solvent)

Spent solvent LHV = 25 GJ/ton

     Water content = 16.5%

   Carbon content = 48% (by dry weight) (See Appendix Table A.1 for carbon content of alternative fuels.)

Coal LHV = 26.3 GJ/ton

Coal carbon emissions factor = 0.68 ton C/ton coal

   Calculation

Spent Solvent carbon emissions factor:

$$1 \; ton \; \times \frac{0.84 \; dry \; ton}{ton} \times \frac{0.48 \; ton \; C}{dry \; ton} = \frac{0.40 \; ton \; C}{ton}$$

C emissions offset per ton coal replaced:

$$\frac{26.3 \; GJ \; / \; ton}{25 \; GJ \; / \; ton} \times \frac{0.40 \; ton \; C}{ton \; sp. \; solv.} - \frac{0.68 \; ton \; C}{ton \; coal} = -0.26 \; ton \; C$$

CO_2 emissions offset per ton coal replaced:

$$-0.26 \; ton \; C \times \frac{44 \; ton \; CO_2}{12 \; ton \; C} = -0.95 \; ton \; CO_2$$

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e.   Local Considerations

The spatial and temporal distribution of biomass is an important factor in assessing the feasibility and potential benefits of utilizing the material in cement manufacturing. In situations where biomass is highly dispersed, such as the case in countries with many small landholders, the transportation costs and associated transport fuel-related emissions may substantially counter the carbon emissions reductions at the cement kiln. In these situations, the net benefits may be greater if biomass is composted and used as soil enrichment, or pelletized for rural heating and cooking. With respect to combustion emissions, biomass does not contain any components that standard cement kiln emissions controls cannot manage.

4. Non-Agricultural Biomass

Globally, non-agricultural biomass accounts for approximately 30% of alternative fuel substitution in cement kilns with animal byproducts including fat, meat and bone meal making up 20% of the total (Cement Sustainability Initiative 2005). Other varieties of non-agricultural biomass include sewage sludge, paper sludge, waste paper, and sawdust. The use of sewage sludge in cement manufacturing is a recent trend; it currently accounts for less than 2% of fuel substitution but is likely to increase in the coming years as wastewater treatment plants become more prevalent, restrictions on the land application of biosolids increase, and landfill space becomes more limited (Fytili 2006). Table II-4 provides a summary of the key characteristics of non-agricultural biomass as alternative fuels for cement manufacturing.

a. Energy Content

Similar to agricultural biomass, there is a wide range in the calorific values reported for non-agricultural biomass-derived waste fuels. Paper sludge, a byproduct of paper production, represents the lower bound with a LHV of approximately 8.5 GJ/dry ton, and sewage sludge the upper bound, at up to 29 GJ/dry ton. The range in calorific values of sewage sludge is enormous and depends on the characteristics of the wastewater that it derives from, and the treatment the sludge receives. Treated sludge, such as that which is anaerobically digested, has a lower energy content than raw sludge (Fytili 2006). Paper is another material with a wide range in calorific values, ranging between 12.5 and 22 GJ/ton. Waste wood and animal byproducts, in relation to other biomass, also have relatively high LHVs on the order of 17 GJ/dry ton. Relative to other fuel substitutes such as petroleum-based wastes and some chemical and hazardous wastes, biomass has a low calorific value. The carbon neutrality of biomass is one incentive for using biomass; however, it requires enormous volumes of biomass to realize substantial conventional fuel offsets.

Table II-4. Characteristics of non-agricultural biomass as alternative fuel

fuel	substitution rate (%)	energy content (LHV) (GJ/dry ton)	water content (%)	carbon emissions factor[b] (ton C/ton)	ΔCO_2[d] (ton/ton coal replaced)	data sources
dewatered sewage sludge	20	10.5-29	75	0.08	-2.5	(Fytili 2006; IPCC 2006; Murray 2008)
dried sewage sludge	20	10.5-29	20	0.24	-2.5	(Fytili 2006; IPCC 2006; Murray 2008)
paper sludge	20	8.5	70	0.2	-2.5	(Maxham 1992; IPCC 1996; European Commission (EC) 2004)
paper	20	12.5-22		0.42	-2.5	(Jenkins, Baxter et al. 1998; European Commission (EC) 2004)
sawdust	20	16.5[a]	20	0.38	-2.5	(Resource Management Branch 1996; Demirbas 2003)
waste wood	20	15.5; 17.4	33.3	0.34	-2.5	(Li 2001; McIlveen-Wright 2007)
animal waste (bone, meal, fat)	20	16-17; 19	15	0.29	-2.5	(Zementwerke 2002; European Commission (EC) 2004)

[a]LHV calculated based on reported HHV
[b]Carbon emission factors calculated using method in Box I-1.
[c]Emissions factor dependent on water content
[d]Change in CO_2 emissions assumed that biomass is carbon-neutral; negative values for change in CO_2 represent a net reduction in emissions.

The quantity of non-agricultural biomass residues that are necessary to replace one ton of coal depends on the residue's energy value and water content. Based on the average values reported in Table II-4, and an assumed coal LHV of 26.3 GJ/ton, the range is between 1.6 and 10.3 tons of biomass residue per ton of coal replaced (Fig. II-3).
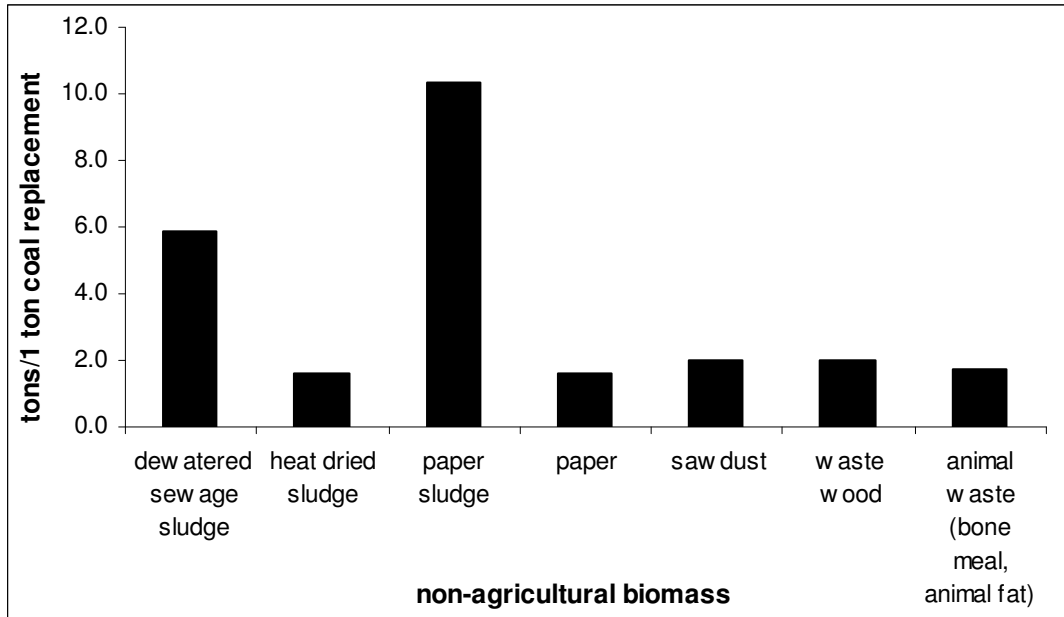
Figure II-3. Tons of non-agricultural biomass residues necessary to replace one ton of coal in a cement kiln. Values are dependent on the material's energy value and water content. Calculations are based on average values reported in Table II-4 and a coal LHV of 26.3 GJ/ton.

b. *Emissions Impacts*

Non-agricultural biomass is considered carbon-neutral for the same reasons discussed above for agricultural biomass. Therefore, the reduction of CO_2 per ton of coal replaced is considered equal for all non-agricultural biomass materials (Table II-4). Of course, for materials such as waste wood and paper sludge, the assumption holds only if the trees have been sustainably harvested, and not sourced from the clearing of old growth forests. Furthermore, the carbon-neutrality only extends to the combustion emissions. The carbon associated with transporting and preparing the biomass (e.g., grinding or shredding,) should be accounted for to get an accurate value for the true carbon offset (or addition.). Carbon emissions reductions associated with the biomass combustion are reported in Table II-4. In addition to possible CO_2 offsets, cement plants burning non-agricultural biomass, including sewage sludge, have documented a subsequent reduction in NO_x emissions from their kilns (McIlveen-Wright 2007; Vallet January 26, 2007).

c. *Key Technical Challenges*

The chlorine present in some non-agricultural biomass, such as treated wood and sewage sludge from wastewater treatment plants, can enhance the volatilization of heavy metals like mercury (Hg), cadmium (Cd) and lead (Pb) (Reijnders 2007). The formation of PCDD/PCDFs is likely to increase if the biomass is contaminated with substances such as paint, pesticides, preservatives, coatings, or anti-fouling agents (UNEP Chemicals 2005). It is believed that their levels are effectively controlled, however, by using the best available incineration technologies and emissions control devices (UNEP Chemicals 2005). See Section 3.d. for other technical challenges associated with the use of biomass in cement kilns.

d. *Local Considerations*

Non-agricultural biomass products are unlikely to be subject to the temporal fluxes in supply that affect agricultural biomass materials. Furthermore, the spatial distribution is likely to be more consolidated than that of agricultural biomass because these products are often processed (e.g., paper sludge, animal by-products.) Decisions regarding the use of non-agricultural biomass as a fuel substitute should be in the context of other potential uses for the material. That is, the waste hierarchy outlined in the guiding principles for using alternative fuels for cement manufacturing should be respected (Table II-1). For example, an alternative productive end use for sewage sludge is land application. If sewage sludge meets the quality standards for use in agriculture (sufficient pathogen reduction and absence of excess levels of heavy metals) it may prove to be the higher value end use. For many other non-agricultural biomass materials the relevant disposal routes are landfilling and other forms of thermal combustion. In comparison to other incineration processes for energy capture, end use in cement manufacturing has the key benefits of utilizing pre-existing infrastructure and enabling the incineration ash to be incorporated into clinker, thus providing a completely closed-loop option.

5. Chemical and Hazardous Waste

Cement plants have been utilizing certain approved hazardous wastes as an alternative fuel since the 1970s. Today, chemical and hazardous wastes account for approximately 12% of global fuel substitution in cement kilns, and include materials such as spent solvent, obsolete pesticides, paint residues, and anode wastes (Cement Sustainability Initiative 2005). Because of the potential for chemical and hazardous wastes to contribute to unwanted emissions, adherence to proper storage and handling protocols is critical for cement kiln operators. There are some hazardous wastes that are presently deemed unsuitable for co-processing in cement kilns including electronic waste, whole batteries, explosives, radioactive waste, mineral acids and corrosives (GTZ and Holcim 2006). These materials could result in levels of air emissions and pollutants in the clinker that are unsafe for public health and the environment (GTZ and Holcim 2006). Table II-5 provides a summary of the key characteristics of chemical and hazardous wastes as alternative fuels for cement manufacturing.

Table II-5. Characteristics of chemical and hazardous wastes as alternative fuel

fuel	substitution rate (%)	energy content (LHV) (GJ/dry ton)	water content (%)	carbon emissions factor[b] (ton C/ton)	ΔCO_2 (ton/ton coal replaced)	data sources
spent solvent		range: 0-40 avg: 25	16.5	0.40	-0.95	(Seyler 2005)
paint residue		16.3	9	0.42	0.06	(Vaajasaari, Kulovaara et al. 2004; Saft 2007)
obsolete pesticides	57	37				(Karstensen 2006)

[a]Carbon emission factors calculated using method in Box I-1.
[b]Emissions factor dependent on LHV and water content, assumes average LHV if range is given

a. Substitution Rate

Because the characteristics of chemical and hazardous wastes vary greatly, it is difficult to generalize about substitution rates in cement kilns. According to the Alternative Solid Fuels Manager at a cement plant in North America, waste fuels are blended together in ratios to match the calorific value of the fossil fuel used at the plant (Loulos April 11, 2008). This approach helps to avoid over-heating in the kiln and minimizes the need for other operating adjustments.

b. Energy Content

In comparison to biomass, chemical and hazardous wastes generally have much higher calorific values. Spent solvent is reported to have a range of LHVs from 0-40 GJ/ton with an average of approximately 25 GJ/ton (Zementwerke 2002; Seyler 2005; Seyler, Hofstetter et al. 2005). An obsolete solvent-based insecticide burned by a cement plant in Vietnam had a LHV of approximately 37 GJ/ton (Karstensen 2006). Paint residues are an exception to the trend, at approximately 16 GJ/ton, they have a calorific value in the same range as biomass (Saft 2007).

The quantity of chemical and hazardous wastes that are necessary to replace one ton of coal depends on the material's energy value and water content. Based on the average values reported in Table II-5, and an assumed coal LHV of 26.3 GJ/ton, the range is between 1.3 and 1.8 tons of chemical and hazardous waste per ton of coal replaced (Fig. II-4).
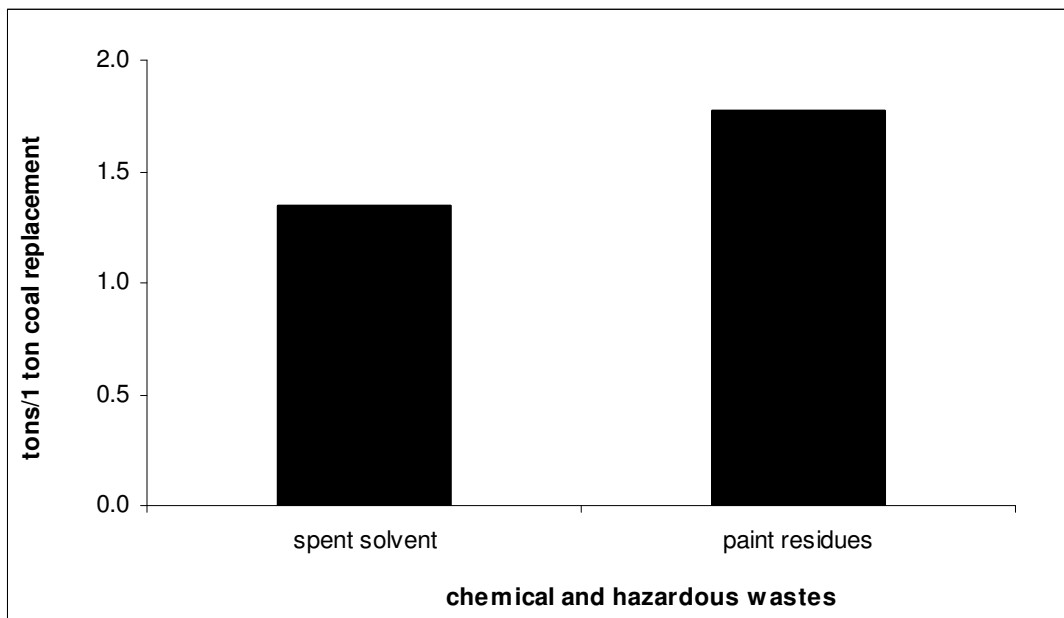
Figure II-4. Tons of chemical and hazardous wastes necessary to replace one ton of coal in a cement kiln. Values are dependent on the material's energy value and water content. Calculations are based on average values reported in Table II-5 and a coal LHV of 26.3 GJ/ton.

Since most chemical and hazardous wastes are liquids, the grinding and shredding step is eliminated and this equates to capital and operational cost savings for the receiving cement plant. Of course, the savings in electricity also improves the net decrease in carbon emissions associated with coal substitution.

c. Emissions Impacts

The change in carbon emissions associated with substituting chemical and hazardous wastes for coal depend on the carbon and water contents, and calorific values of the waste alternatives in comparison to coal. Unfortunately, there is little published information on the carbon contents of most of these materials, making it difficult to generalize their impacts on carbon emissions. However, most of these chemical and hazardous wastes embody a wide range of materials (e.g., spent solvent, pesticides), thus individual case studies would likely have limited utility in representing combustion characteristics. Furthermore, for health and safety permitting, and to anticipate the necessary changes in the cement manufacturing processes, it is essential that the precise materials being considered as alternative fuels undergo thorough chemical analysis before being used in cement kilns. As seen in Table II-5, assuming an average LHV for spent solvent, the avoided CO_2 emissions is substantial at -0.95 t CO_2/t coal replaced. On the other hand, the use of paint residue to replace coal leads to a small but positive addition of CO_2.

The production of toxic and/or environmentally harmful emissions is a widespread and valid concern related to the incineration of hazardous materials. Emissions tests published by the US EPA in the 1980s and 1990s suggested that the PCDD/PCDF emissions from plants burning hazardous wastes were unequivocally worse than kilns using traditional fuels. However, the current validity of those results has been called into question on a number of grounds: 1. The kilns burning hazardous fuels were tested under 'worst-case' scenarios in order to establish the upper boundaries of possible emissions; 2. Long wet and long dry kilns without exit gas cooling were the predominant technology at the time and they are known to have higher emissions (WBCSD 2002; Karstensen 2008). According to Karstensen, more recent studies on preheater/pre-calciner dry process kilns conducted by the Thai Pollution Control Department and UNEP, Holcim Columbia cement manufacturing, and researchers in Egypt have all found non significant increases in PCDD/PDCF emissions compared to the baseline coal-fired kilns, and all fell well within compliance standards (Karstensen 2008). In regions, such as China, where VSKs are still the dominant technology, the EPA's study from the 1980s and 1990s remains quite relevant and caution should be exercised to prevent an increase in dioxin emissions through the introduction of alternative fuels. Currently, compliance with the US EPA's "Brick MACT" (maximum achievable control technology) rule on PCDD/PCDF emissions is achieved by combining low temperatures in the air pollution control device (APCD), low carbon monoxide, chlorine bypasses, and elevated oxygen (US Environmental Protection Agency 2008). In wet kilns, flue gas quenching to reduce APCD temperatures has been shown effective (Karstensen 2008).

Importantly, since the 1990s, researchers and cement plant operators have come to better understand the minutiae of emissions characteristics associated with using hazardous wastes as alternative fuel. Research on the combustion of hazardous wastes indicates that the potential for PCDD/PCDF formation in cement kilns is limited to the cyclone

preheater and the post-preheater zones, the coolest zones of the system (UNEP Chemicals 2005; Karstensen 2008). Kiln injection protocols have been developed to avoid harmful emissions: chemical and hazardous waste fuels that are free of organic compounds may be added to the raw slurry or mix, and materials with high organic contents must be introduced directly into the main burner, the secondary firing, or to the calcining zone of a long wet or dry kiln. Following these loading schemes will prevent the formation of harmful emissions such as PCDDs (Karstensen 2008). It is also essential that materials are fully combusted, thus retention time, mixing conditions, temperature, and oxygen content must be carefully monitored and adjusted as necessitated by the waste fuel's heating value. The sulphur content in coal has been shown to reduce PCDD/PCDF emissions; co-firing hazardous wastes with coal is desirable (Karstensen 2008). Cement kiln incineration criteria for the co-firing of hazardous wastes have been established by the US and EU and are sufficient to achieve emissions compliance.

Table II-6. Cement kiln criteria in the US and EU for co-processing hazardous waste

	temperature (°C)	**burning time (s)**	**oxygen (%)**
US (TSCA PCB)	1200	2	3
EU (Directive 2000/76/EU) non-chlorinated hazardous waste	850	2	-
EU (Directive 2000/76/EU) chlorinated hazardous waste (>1%)	1100	2	2

d.   Key Technical Challenges

Different types of hazardous wastes require different handling arrangements. A cement manufacturing plant in the US has three different systems for receiving and injecting hazardous wastes: one for pumpable wastes, one for containerized wastes, and a bulk pneumatic loader for solid wastes (Harrell March 4, 2008). With respect to pumpable wastes, consideration must be given to the ambient viscosity of the material, as some wastes may require heating to be pumpable. Heaters can be incorporated into the pumping system at an additional cost.

If not handled appropriately, the co-firing of chemical and hazardous wastes has potentially dangerous environmental and human health consequences. A plant operator in the US with experience using hazardous wastes emphasizes the importance of using a fully automated and mechanized handling system, not human labor to inject the waste into the kiln (Harrell March 4, 2008). In keeping with the guiding principles for good practice in fuel substitution (Table II-1), cement plants that accept hazardous wastes must have sufficient technical capacity and infrastructure to ensure worker safety and the safety of their surrounding environment. For example, this entails a conveyance system for transferring wastes from their delivery to storage containers, a safety cutoff/bypass to prevent overflow of liquid waste containers (Bech 2006). While accepting hazardous waste requires a new set of skills in comparison to using coal or other conventional fuels, it is not necessarily more complicated (Harrell March 4, 2008).

e.   Local Considerations

Cement plants considering the use of hazardous wastes should carefully evaluate the risks involved, including those associated with public perception, as well economic and environmental. In the US, cement plants receive a tipping fee to accept hazardous waste

to offset the investment cost of the handling infrastructure and to provide a positive return on investment for their willingness to take on added production risks (Harrell March 4, 2008).

6. Petroleum-Based Fuels

Globally, approximately 30% of waste-based fuels are derived from petroleum products including tires, waste oils, rubber, plastics, petroleum coke (petcoke), and asphalt (Cement Sustainability Initiative 2005). Among these fuels, tires and waste oils are the most common. Table II-7 provides a summary of the key characteristics of petroleum-based fuels as alternative fuels for cement manufacturing.

TableII-7. Characteristics of petroleum-based wastes as alternative fuel

fuel	substitution rate (%)	energy content (LHV) (GJ/dry ton)	carbon emissions factor[a] (ton C/ton)	ΔCO_2[b,c] (ton/ton coal replaced)	data sources
tires	<20	28; 37	0.56	-0.8	(ICF Consulting 2006)
polyethylene	unavailable	46	0.70	-1.0	(Subramanian 2000; ICF Consulting 2005)
polypropylene	unavailable	46	0.70	-1.0	(Subramanian 2000; ICF Consulting 2005)
polystyrene	unavailable	41	0.70	-0.9	(Subramanian 2000; ICF Consulting 2005)
waste oils	unavailable	21.6	0.44	-0.5	(Mokrzycki, Uliasz-Bochenczyk et al. 2003; IPCC 2006)
petroleum coke	up to 100	19; 34	0.78	0.2	(Kaplan 2001; Mokrzycki, Uliasz-Bochenczyk et al. 2003; Kaantee, Zevenhoven et al. 2004)

[a]Carbon emission factors calculated using method in Box I-1.
[b]Change in CO_2 calculated assuming average LHV when range is given.
[c]Negative values for change in CO_2 represent a net reduction in emissions; positive values represent a net addition of CO_2 emissions.

Regarding waste oil, 1 billion gallons are collected every year in the US; 75% is marketed directly as fuel oil, 14% is refined and 11% is distilled (Boughton 2004). In the EU, of the approximately 1.7 million tons of waste oil collected every year, 63% is used by cement kilns. About half of the waste oil used by cement kilns in the EU is treated prior to use, while the other half is used as a secondary fuel without treatment (Gendebien 2003).

The use of tires by cement plants has increased dramatically over recent decades: in 1991 nine plants in the US were burning tires and by 2001, 39 plants were using discarded tires for fuel (Schmidthals and Schmidthals 2003). By 2005, 58 million tires were burned in 47 cement facilities around the US (RMA 2006). Similar trends have evolved in the EU

largely driven by policies banning whole tires in landfills as of 2003, and shredded tires as of 2006 (Corti and Lombardi 2004). The German Federal Environmental Office commissioned a study in 1999 to evaluate the trade-offs among different landfill alternatives for scrap tire and found that among thermal utilization processes, cement kilns are the optimal choice (Schmidthals and Schmidthals 2003).

a. Substitution Rate

Tires are typically substituted for up to 20% of the fuel demand, higher substitution rates can lead to overheating in the kiln and to a reducing atmosphere that facilitates formation of volatile sulphur compounds (Schmidthals and Schmidthals 2003). Published substitution rates were not found for any other petroleum-based waste fuels.

b. Energy Content

Petroleum-based waste fuels have high calorific values, ranging from approximately 19 GJ/ton for some petcoke to 46 GJ/ton for some plastics. As with other alternative fuel categories, the range in heating values reported in the literature for specific types of petroleum-based fuels is large. For example, an Australian tire study found a LHV equivalent to 27.8 GJ/ton for passenger tires, whereas a Clean Development Mechanism project at a cement kiln in Tamil Nadu, India reports a LHV of 37.1 GJ/ton (Atech Group 2001) (Grasim Industries Ltd-Cement Division South 2005). Petcoke also appears to have a wide ranging LHV: Mokrzycki reports 18.9 GJ/ton for petcoke used by a cement plant in Poland (Mokrzycki, Uliasz-Bochenczyk et al. 2003), whereas both Kaantee et al. and Kaplan et al.report LHVs of approximately 34 GJ/ton (Kaplan 2001; Kaantee, Zevenhoven et al. 2004). Different varieties of plastic are found to have LHVs ranging from approximately 29-40 GJ/ton (Gendebien 2003).

The quantity of petroleum-based wastes that are necessary to replace one ton of coal depends on the material's energy value and water content. Based on the average values reported in Table II-7, and an assumed coal LHV of 26.3 GJ/ton, the range is between 1.3 and 1.8 tons of chemical and hazardous waste per ton of coal replaced (Fig. II-5).

Iron is a necessary input into clinker manufacturing. When tires are used as an alternative fuel, approximately 250 kg Fe/ton tires is recovered, reducing the quantity required from mineral sources (Corti and Lombardi 2004).
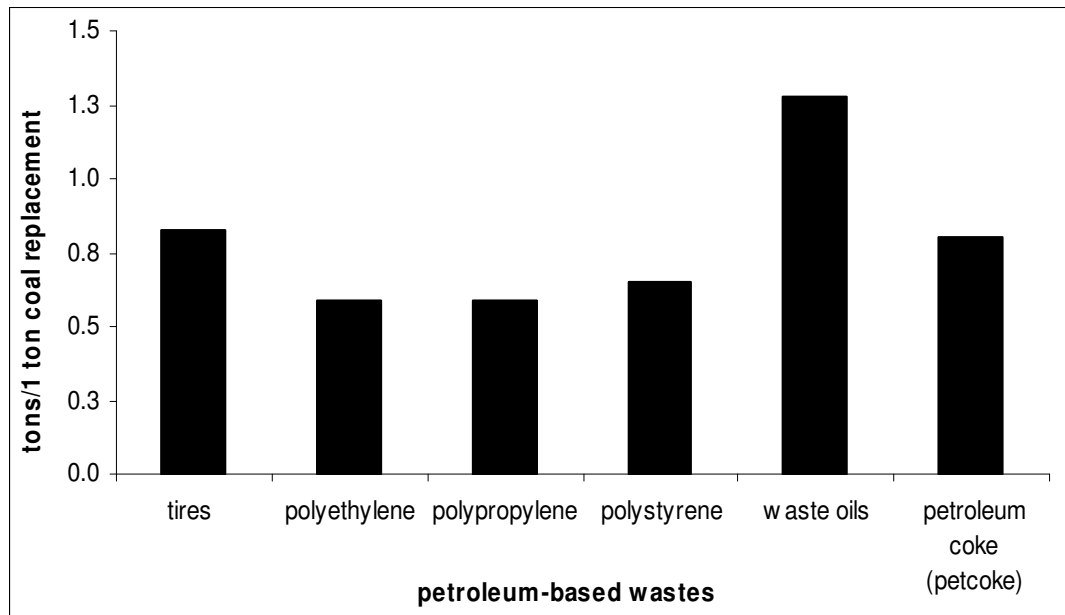
Figure II-5. Tons of petroleum-based wastes necessary to replace one ton of coal in a cement kiln. Values are dependent on the material's energy value and water content. Calculations are based on average values reported in Table II-5 and on a coal LHV of 26.3 GJ/ton.

c. Emissions Impacts

The carbon offsets associated with replacing coal with petroleum-based waste fuels are highest for polyethylene and polystyrene plastics, at approximately -1.0 tons CO_2/ton coal, waste oils and tires yield carbon offsets of approximately -0.5 and -0.8 tons CO_2/ton coal, respectively. On the other hand, the use of petcoke as a coal replacement results in a net carbon contribution of approximately 0.21 tons CO_2/ton coal. Petcoke results in a net increase in CO_2 because it has a higher carbon emissions factor and lower calorific value than coal.

Sulphur and NO_x emissions can also be problematic for some petroleum-based waste fuels. Petcoke typically has a high sulphur content of 4-7% on a dry basis as compared to coal which has an average sulphur content of 1.2%, and petcoke's low volatile matter content is reported to contribute to NO_x emissions (Kaplan 2001). On the other hand, using tires can decrease NO_x emissions. In the US, the EPA required states to develop plans for reducing NO_x emissions and requiring cement kilns to use tires in place of conventional fuels is seen as an effective and low-cost option (RMA 2006).

d.   Key Technical Challenges

In practice, tires are injected either whole or as shreds into cement kilns. According to the experiences of cement plant operators, whole tires seem to be the economically and technically superior option, particularly for long dry kilns (McGray February 18, 2008). The capital cost of the shredding equipment and the operational energy demands, can render using tires an expensive undertaking rather than one that is cost-saving (McGray February 18, 2008). For other solid varieties of petroleum-based waste, such as plastics and rubber, shredding before injection and co-firing in the cement kiln is the norm (Cement Sustainability Initiative 2005).

Whether shredded or whole, tires are typically injected mid-kiln into the pre-calcination phase and the remaining steel and ash are incorporated into the clinker. Tires can be substituted at a rate of 20% or less; higher rates can cause instability and overheating in the kilns, and can also lead to a reduced atmosphere which facilitates the formation of volatile sulphur compounds (Schmidthals and Schmidthals 2003). Tires can substantially decrease kiln NO_x emissions, as long as stability in the kiln is maintained. If stability is lost, NO_x and other emissions from the kiln can substantially increase, and production capacity can be impaired (McGray February 18, 2008). Based on the experiences of a number of cement plants in the US, a fully automated tire injection system is critical to the successful use of tires (McGray February 18, 2008). Automated equipment adds to the initial capital cost, however, it pays for itself by ensuring uniform tire injection which is essential for kiln stability.

With respect to emissions, NO_x and chlorine compounds are of potential concern when burning petroleum based waste for fuel. Chlorine is a problem in certain plastic varieties, particularly PVC (polyvinyl chloride). When incinerating chlorine-containing plastics, a bag filter can be used to capture the chlorine particles which can later be input into the clinker (Lafarge 2007). Chlorine may impact the quality and strength of the clinker if concentrations exceed 0.7% (Herat 1997). In comparison to crude based heavy fuel oils, waste oil is far more concentrated with heavy metals, sulfur, phosphorus, and total halogens (Boughton 2004). The poor environmentally quality of waste oil is evidenced by the fact that of that collected in California and marketed as fuel, only 3% is consumed in-state. The rest of the waste oil is shipped out-of-state or overseas because it does not meet local air quality regulations (Boughton 2004). Despite the fact that distillation and refining are costly processes, the environmental impacts of burning untreated waste oil are significant, thus the practice cannot be recommended for cement kilns or other incinerators (Boughton 2004).

e.   *Local Considerations*

As addressed in the guiding principles for good practice in alternative fuel substitution (Table II-1), the costs and benefits of using petroleum-based wastes as alternative fuels in cement manufacturing should always be compared against other local disposal and end-use options. For example, where the infrastructure for plastic recycling exists, remanufacturing into new plastic products is likely higher in the waste hierarchy, and thus likely environmentally preferable option with respect to resource conservation (Siddique, Khatib et al.). However, plastic recycling centers are a common source for plastic scrap to be used in cement kilns. In comparison to dedicated waste to energy incineration, burning plastics in cement kilns eliminates the challenge of disposing of incineration ash since it can be incorporated into clinker. Landfilling plastic ash is often prohibited because the embodied heavy metals can leach and pose a threat to groundwater (Siddique, Khatib et al.).

In the US, cement kilns are either paid a fee ($0.05-$0.10/tire) to accept tires, or they receive them for free (McGray February 18, 2008). Cement kiln operators stress the importance of contracting with a tire recycler that will reliably supply clean tires that are free of rims and other automotive components (McGray February 18, 2008).

7. Miscellaneous Fuels

There are a variety of miscellaneous waste fuels such as automobile shredder residue (ASR), carpet residue, textiles, wax residue, landfill gas, and municipal solids waste (MSW) that are burned in cement kilns. Table II-8 provides a summary of the key characteristics of miscellaneous wastes as alternative fuels for cement manufacturing.

Table II-8. Characteristics of miscellaneous wastes as alternative fuel

fuel	substitution rate (%)	energy content (LHV) (GJ/dry ton)	water content (%)	carbon emissions factor[a] (ton C/ton)	ΔCO_2[b,c] (ton/ton coal replaced)	data sources
automobile shredder residue (ASR)	2	16.5	2	0.44	0.05	(Mirabile, Pistelli et al. 2002)
carpet residue polypropylene nylon	unavailable	28 17	0.2 0.9	0.57 0.42	-0.54 -0.15	(Realff 2005)
textiles	30	16.3	6	0.42	-0.0	(Ye, Azevedo et al. 2004)
landfill gas	unavailable	19.7		0.30	-1.0	(Asian Development Bank 2006)
municipal solid waste (MSW)	up to 30	12-16	10-35	0.26-0.36	-0.4	(European Commission (EC) 2004; IPCC 2006)

[a]Carbon emission factors calculated using method in Box I-1.

[b]Change in CO_2 calculated assuming average LHV when range is given.

[c]Negative values for change in CO_2 represent a net reduction in emissions; positive values represent a net addition of CO_2 emissions..

Globally, refuse derived waste accounts for approximately 1% of the alternative fuels used in cement kilns (Cement Sustainability Initiative 2005). ASR, otherwise known as fluff, is the term for the non-recoverable components of end-of-life vehicles. It is typically about 20% by weight of the vehicle and is an amalgam of rubber, plastic, wood, paper, dirt, fabric, and ferrous and non-ferrous metal pieces (US EPA 2007). Every year approximately 27 million vehicles are retired from the road, and in the US alone, 3-5 million tons of ASR ends up in landfills (Boughton 2006; US EPA 2007). ASR is co-fired in cement kilns in Belgium, among other countries (Gendebien 2003; Boughton 2006). The practice of using ASR in cement kilns has potential to increase in Europe due to recent policy directives on the disposal of vehicles. The EU End-of-Life Vehicle Directive (2000/53/EC) requires that at least 85% of cars be reused or recycled (including for energy recovery) by 2006, and 95% by 2015 (Christen March 22, 2006).

Carpet is by design made to be highly durable, thus recycling it is technically challenging and energy intensive (Realff 2005). Every year in the US, an estimated 2 M tons of carpet are disposed of in landfills and the rate of disposal is expected to increase at 3% per annum over the next decade (Realff 2005). Alternatively, carpet residues may be an

appealing alternative fuel for cement kilns because of their high embodied energy content and high fraction of calcium carbonate which is incorporated directly into the clinker.

In the UK, textiles make-up about 3% of municipal waste stream but the most potential for recovery is via direct donation to clothing banks and door-to-door collection. About 7% of donated textiles are diverted to waste (Ryu, Phan et al. 2007). MSW must be sorted to remove the recyclable and inert, and sometimes wet fractions before it is input into cement kilns (Gendebien 2003). The remaining material accounts for approximately 20-50% of the original MSW weight, and can be incinerated directly or pelletized (Gendebien 2003). The product of MSW processing is typically referred to as "residue derived fuel" (RDF), and is a common fuel alternative in many European countries. Italy, Belgium, Denmark and The Netherlands are among the nations that have at least one cement kilns processing RDF (Gendebien 2003).

a. Substitution Rate

Appropriate substitution rates vary among the miscellaneous fuels described above. At the lower end of the spectrum, ASR can be substituted at a rate of only 2% before significantly raising operation and maintenance costs of cement manufacturing (Mirabile, Pistelli et al. 2002). On the other hand, textiles can be substituted at a rate as high as 30% (Ye, Azevedo et al. 2004).

b. Energy Content

ASR, textiles, and MSW, all have LHVs of approximately 16 GJ/ton. Landfill gas has a slightly higher LHV of approximately 19 GJ/ton. The LHV of carpet residues depends on the carpet type: polypropylene and nylon carpet residues have LHVs of approximately 28 and 17 GJ/ton, respectively (Realff 2005).

The quantity of miscellaneous wastes that are necessary to replace one ton of coal depends on the material's energy value and water content. Based on the average values reported in Table II-8, and an assumed coal LHV of 26.3 GJ/ton, the range is between 0.9 and 2.3 tons of miscellaneous waste per ton of coal replaced (Fig. II-6)
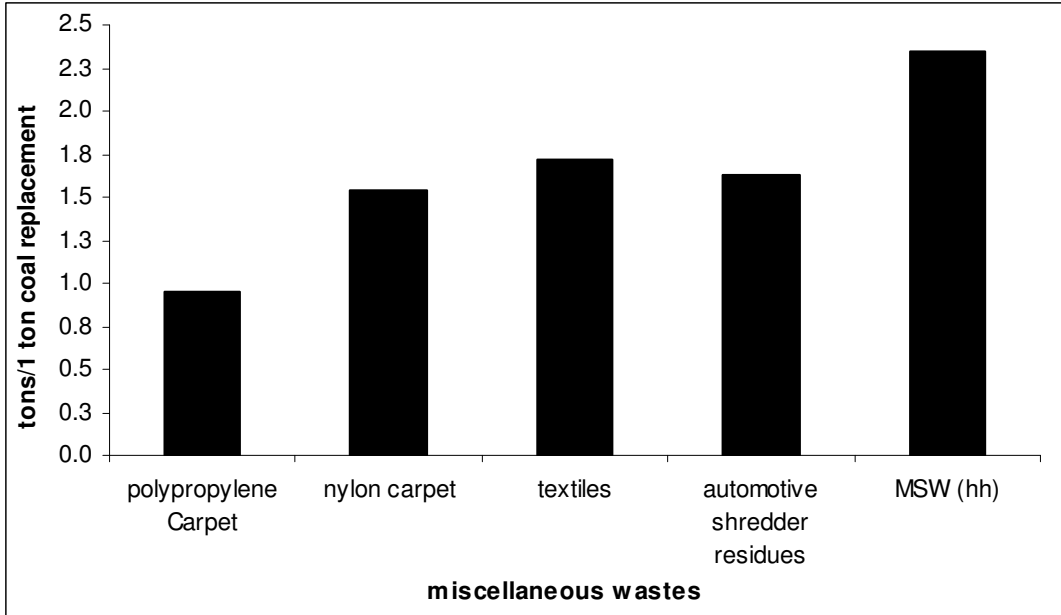
Figure II-6. Tons of miscellaneous wastes necessary to replace one ton of coal in a cement kiln. Values are dependent on the material's energy value and water content. Calculations are based on average values reported in Table II-8 and on a coal LHV of 26.3 GJ/ton.

c. Emissions Impacts

The carbon emissions impacts of substituting miscellaneous waste fuels for coal vary based on their respective calorific values and carbon and water contents. Textiles and ASR, with similar calorific values and carbon contents, both have virtually zero net impact on carbon emissions in comparison to coal. Carpet residues contribute non-trivial carbon offsets of about -0.15 and -0.54 tons CO_2/ton coal for nylon and polypropylene carpet residues, respectively. Among the fuels in this category, landfill gas has the highest carbon offset potential, -1.0 tons CO_2/ton coal. For a net carbon offset through the replacement of coal with MSW, water content must be less than 15% assuming an average MSW LHV of 14.5 GJ/dry ton.

In addition to their lower energy content and carbon offset potential, nylon compared to polypropylene carpet residues have much higher NO_x emissions. The former contain approximately 4.5% nitrogen by mass, opposed to less than 0.05% for polypropylene residues (Realff 2005). Both varieties of carpet residue increase nitrogen emissions in comparison to coal, the latter only slightly dues to an increase in the kiln's flame temperature (Realff 2005). Conversion of the nitrogen in nylon carpet residues to NO_x emissions is more effectively controlled by batch-fed injection schemes than continuous feed (Realff 2005).

d. Key Technical Challenges

There are several challenges associated with using ASR in cement kilns. It is a highly heterogeneous product which makes maintaining kiln stability difficult, and which has led many cement manufacturers to resist accepting it. ASR also tends to have high alkalinity, due to potassium and calcium, which increases cement kiln dust (CKD)

generation. Burning ASR may lead to higher heavy metal emissions due to the presence of copper wire; the common presence of PCBs in ASR is also a barrier to its use as a fuel (Boughton 2006). While there are cement manufacturers that are currently willing to accept ASR, (particularly when paid,) the degree to which the environmental benefits outweigh the costs of incinerating ASR that is not carefully separated, is unclear (Boughton 2004).

There are opportunities for making the use of ASR in cement kilns beneficial to both society and the cement plants. Automobile recyclers are working on developing technologies to improve the separation of materials in ASR and to make its combustion characteristics more kiln-operator and environmentally friendly (Boughton 2006; Christen March 22, 2006). Experimental results suggest that existing ASR density separation technologies that exclude fine material (<1.2 cm) can significantly reduce problems with CKD and harmful emissions (Boughton 2004). The estimated annualized capital cost of the necessary equipment over a 20-year time horizon is $155,000 for a 15 t/hour facility (Boughton 2004).

Processing MSW prior to incineration is an important step for limiting the heterogeneity of the waste, and to enable its stable burning in the cement kiln. Mechanical sorting is reported to be a sufficient processing technique by plants in Austria, Germany and Italy, while in The Netherlands, pelletizing is practiced (Gendebien 2003). The heterogeneity of MSW makes its emissions characteristics hard to generalize. There are wide ranges in the literature with respect to the potential heavy metal emissions associated with RDF; Genon and Berzio (Genon 2008) summarized the ranges from numerous databases, and a subset of their findings is reproduced in Table II-9. Genon and Berzio found in one simulation of substituting 50% of coal with RDF that emissions from heavy metals Cd and Hg actually improved; however, in a subsequent simulation using a different set of RDF characteristics, the emissions upon substitution were significantly worse (Genon 2008). An environmental impact assessment by the European Commission generally concluded that substitution of conventional fuel with RDF in cement kilns has an overall positive impact – largely due to savings in GWP – but that certain emissions (e.g., Hg, Cd, SO_2) increase (Gendebien 2003). It should be noted that among the thermal incineration processes considered in the European Commission's analysis, (coal-fired power plants using brown and hard coal, dedicated MSW incinerators,) cement plants performed the best (Gendebien 2003).

Table II-9. Heavy metal concentrations found in RFD (refuse derived fuel). Reproduced from Genon and Berzio 2008 (Genon 2008)

heavy metal	min (ppm dry)	max (ppm dry)
Sb	9	14.7
As	0.9	8.8
Cr	11.3	140
Mn	28	210
Hg	0.1	0.4
Ni	0.85	21
Pb	25	157
Cu	45	266
Sn	4	500
Zn	225	340

Studies have shown that ASR can consist of up to 40% of the mineral equivalent of the inputs in cement manufacturing (e.g., silicates, calcium, aluminum, and iron) (Boughton 2006). Taking advantage of these elements can reduce the environmental and economic costs associated with mining them. Furthermore, the combustion of ASR in cement kilns can lead to substantial savings in landfill space. Existing ASR separation technologies are not able to recover more than approximately 80% of vehicles fractions; however, existing technologies can be employed to separate ASR into size fractions that are acceptable for cement kilns to use as alternative fuel (Boughton 2004).

f.   *Local Considerations*

Many of the miscellaneous waste fuels discussed above have several possible end uses, an evaluation of the local context is necessary for choosing the most appropriate one. For example, ASR contains materials that can be recycled into new materials. Similarly, the nylon in nylon carpet residues is very valuable a raw material if it can be effectively extracted from the residues.

III. China: Alternative Fuel Availability and Feasibility of Co-Processing in Cement Kilns

1. Introduction
China is the world's largest cement manufacturer, accounting for 44% of global production (Price 2007). In 2007, China produced 1.36 billion tons of cement in more than 5000 cement plants throughout the country (Cui April 2008) While they may be the volumetric leaders in cement manufacturing, there are several opportunities for China to improve the environmental sustainability of their cement sector by learning from the best practices that have emerged in other countries, particularly in the EU and the US.

There are several efforts underway to decrease reliance on fossil fuels, and to reduce the global warming impact of cement production in China. For example, the National Development and Reform Commission (NDRC) has outlined several measures for improving energy efficiency including increasing the share of dry process kilns, consolidating the industry and eliminating the most inefficient producers, and recovering waste heat for electricity production at cement plants (Price 2007). These efforts come on the heels of new energy efficiency standards (Cement Plant Energy Efficiency Design Specification) passed by the Ministry of Construction in China in November 2007. The new standards apply to cement plants with a capacity of greater than 4000 t/day and built after 2005; these facilities must reduce total energy use by 15% in comparison to plants built between 2001 and 2005. The energy reductions encompass the entire lifecycle of cement manufacturing and aim to reduce the industry's total environmental impact.

To date, few Chinese cement manufacturers use alternative fuels. Co-processing such fuels at cement plants in China is a way to enhance the marginal benefits of energy efficiency gains that result from other efforts mentioned above. Section II of this report detailed the types of waste fuels that are currently being used to replace conventional fuels in cement manufacturing around the world. What follows is an assessment of the availability of alternative fuels in China (spatially and temporally), a description of relevant policies that could act to incentivize or create barriers to the use of alternative fuels in cement manufacturing, and an assessment of the geographic distribution of cement manufacturers. The intent of this section is to help guide the design of a feasible and successful demonstration project in China. The emphasis is on the feasibility of co-processing biomass residues, for which the most information is available. However, the availability of other waste fuels is also discussed.

2. Agricultural Biomass
The use of agricultural biomass residues as a fuel substitute in cement manufacturing appears to be highly promising for China based on its widespread availability, and the current underutilization of biomass residues. In 2000, biomass (including agricultural, forest, and municipal solid waste) accounted for 13% of China's primary energy consumption (Li 2001). The use of biomass is concentrated in rural areas where many households burn it directly for cooking and heating; 60% of rural households use straw as a primary energy source (National Bureau of Statistics of P.R. China 2008). However, in

recent years, there has been a significant trend among rural households away from biomass, and towards coal and petroleum products as well as electric power (Li 2001). Simultaneously, the Chinese government has become very interested in utilizing biomass residues as an energy source in more large-scale, centralized waste-to-energy facilities (Liao 2004).

A recent study by Liao et al. estimated the provincial-level distribution of biomass residues throughout China, and also approximated the amount of unused residue in each province (reproduced in Appendix B.2) (Liao 2004). The estimated residue yields are based on crop-specific coefficients derived by the Chinese Ministry of Agriculture and the US Department of Energy (MOA/DOE) which the authors multiplied by the actual crop yields. Similarly, the estimations of unused residues are based on average utilization rates identified by the MOA/DOE researchers (Liao 2004). Using information on the provincial-level availability of agricultural biomass residues and the LHV of each crop, we determined that the greatest energy is available in rice straws, wheat straws, and corn stalks. Other important agricultural biomass feedstocks include residues from sorghum wheat, hemp stems, rapeseed stems, cotton stalks, and soybean stems and leaves. Figure III-1 shows the total annual energy value (GJ) of unused biomass residues in the ten provinces in China with the greatest biomass production.

The feasibility of using biomass residues in cement manufacturing is in part dependent on the proximity of cement plants to the residues. Figure III-1 shows the magnitude of cement production in each of the ten provinces with the highest value of unused biomass residue. Based on the criteria of large availability of biomass and a substantial cement industry, Henan Province in south-central China, is worthy of consideration. Henan accounted for approximately 6% of China's cement production in 2006 and if all of the unused agricultural biomass residues were utilized in cement kilns it would off-set about 16,000 tons of coal out of the approximately 10.3 million tons used in the province to make cement (Table III-1) (National Bureau of Statistics of P.R. China 2007). South-central and southern China, in general, appears to be a promising geographic region with significant biomass energy availability and cement manufacturing in Hubei, Hunan, and Guangxi (Table III-1, Figure III-2). Among the provinces considered, Shandong province in eastern China has the highest cement production; the coal equivalent of using all unused agricultural biomass residue in Shandong in cement kilns is approximately 6400 tons. On the other hand, Xinjiang province has the greatest availability of unused biomass, yet very little cement production.

The comparisons made between agricultural biomass availability and the distribution of cement production can be used to coarsely identify locations where the practice of using the residues in kilns is likely to be most feasible. We specifically report the availability of unused biomass residues to acknowledge existing productive uses. One important and high value use of biomass residues in China is paper production. China has the third largest paper industry in the world, and manufactures two-thirds of all non-wood papers (Hammett 2001). Within the waste hierarchy, the use of biomass residues in paper making would supersede their use in cement manufacturing.

Planning for the use of biomass residues in cement manufacturing entails several measures of feasibility. First it should be confirmed that the biomass residues in question are not being put to a more environmentally or economically beneficial use. The next steps toward determining the best location for such an endeavor entails a finer analysis of the proximity of cement plants in the region to agricultural fields; assessment of the willingness and capacity of cement plants to utilize biomass residues; assessment of any regulatory incentives or barriers to biomass collection and combustion in kilns; and analysis of the temporal distribution of biomass residues. A local crop schedule should be made to determine the extent to which biomass residues can serve as a year-round fuel substitute. See Appendix B.1 for biomass energy values disaggregated by crop type and province. Some provinces may have a climate and crop portfolio that yields a constant supply of biomass residues whereas in other regions the residue supply may be more seasonal.

Table III-1. Availability and energy value of unused biomass residues by province

province	primary types of biomass residues	total energy value of unused residues (GJ)	coal eq. (tons)	2006 cement production (Mt)
Xinjiang	wheat straw, corn stalks, cotton stalks rice straw	4.7×10^5	1.8×10^4	12.2
Henan	wheat straw, corn stalks, cotton stalks rice straw, soybean stems, rapeseed stems	4.2×10^5	1.6×10^4	76.1
Hunan	rice stalks, rapeseed stems, corn stalks,	3.7×10^5	1.4×10^4	45.9
Guangxi	rice stalks, sugarcane leaves, corn stalks, soybean stems	3.2×10^5	1.2×10^4	36.6
Hubei	rice stalks, wheat straw, corn stalks, rapeseed stems, cotton stalks	2.9×10^5	1.1×10^4	52.0
Jilin	corn stalks, rice stalks, soybeam stems	2.7×10^5	1.0×10^4	18.0
Hebei	corn stalks, wheat straw, soybean stems, cotton stalks	2.1×10^5	8.0×10^3	86.3
Inner Mongolia	corn stalks, wheat straw, soybean stems, sunflower stalks	1.9×10^5	7.1×10^3	22.1
Shandong	corn stalks, wheat straw, soybean stems, rice stalks, cotton stalks	1.7×10^5	6.4×10^3	166.7
Shanxi	corn stalks, wheat straw	1.5×10^5	5.7×10^3	26.8
China total	corn stalks, wheat straw, rice stalks, cotton stalks	4.1×10^6	1.6×10^5	1236.8

Figure III-1. Total annual energy value (GJ) of unused biomass residues in the ten provinces in China with the greatest biomass production. The total annual value of unused biomass residues in China is 1.6×10^5 GJ. The top ten provinces account for 70% of the biomass residue energy value.

Figure III-2. Map of China showing cement production (in million tons in 2006) in the top-ten biomass and forest residue producing provinces, respectively.
(Unlabeled map from: www.sinopro.com/images/china_map.gif)

3. Non-Agricultural Biomass

As discussed in the overview of alternative fuels for cement manufacturing, non-agricultural biomass encompasses a range of materials including wood/forest residues, sewage sludge, paper residues, and animal waste.

a. Forest Residue

Liao et al. also approximated the provincial-level distribution of forest residues for different forest types throughout China (see Appendix B.4 for reproduction of their data). The values for their residue yields are based on coefficients derived in an earlier study by Zhijie Huang (Liao 2004). The researchers based their estimations of unused residues on data from the National Bureau of Statistics of China (Liao 2004). We have taken the provincial-level availability of forest biomass residues and used the LHV of wood residue to determine the energy availability, and the potential for coal replacement (Table III-2). See Appendix B.3 for forest residue energy values disaggregated by crop type and province.

Based on the criteria of having a large potential for forest biomass utilization and a substantial cement industry, Guangdong province in southeastern China, appears to be a promising location for forest residue substitution for coal in cement manufacturing. Guangdong has the highest cement production among the provinces under consideration (and accounted for 8% of China's production in 2006,) and has substantial availability of forest residues (Table III-2, Figs. III-2 and III-3). Yunnan and Sichuan provinces also appear to have a favorable combination of forest residues and cement manufacturing; if all residues in either province were used in cement kilns it would offset between 9.5 and 10 million tons of coal (Table III-2, Fig. III-2).

Table III-2. Availability and energy value of unused forest residues by province

province	primary types of forest residues	total energy value of unused residues (GJ)	coal eq. (tons)	2006 cement production (Mt)
Heilongjiang	timber stand, sparse forest, firewood forest	4.2×10^8	1.6×10^7	14.8
Inner Mongolia	timber stand, shrubs, sparse forest	3.7×10^8	1.4×10^7	22.1
Yunnan	timber stand, shrubs, sparse forest, firewood forests, protected forests	2.7×10^8	1.0×10^7	33.1
Sichuan	timber stand, shrubs, protected forest, sparse forest	2.5×10^8	9.5×10^6	50.6
Jilin	timber forest	1.3×10^8	4.9×10^6	18.0
Shaanxi	orchard, special use forest, timber forest, sparse forest	7.9×10^7	3.0×10^6	25.2
Hubei	orchard, timber forest, special use forest, sparse forest	5.1×10^7	1.9×10^6	52.0
Guangdong	timber stand, sparse forest, firewood forest	4.4×10^7	1.7×10^6	97.0
Gansu	orchard, special use forest, sparse forest	4.0×10^7	1.5×10^6	14.5
Shanxi	timber forest, shrubs	3.1×10^7	1.2×10^6	26.8
China total	timber forest, shrubs, sparse forest, firewood forest	1.6×10^9	6.1×10^7	1236.8

The above comparison between forest residue availability and cement manufacturing in China is intended to provide a coarse assessment of the locations where biomass fuel substitution is likely to be most feasible. The next step towards implementation is a finer analysis of the dispersal of the forest residues throughout a given province; assessment of the collection and transportation logistics; determination of the willingness and technical capacity of local cement plant to burn the forest residues in their kilns; and investigation of any regulatory incentives or barriers.
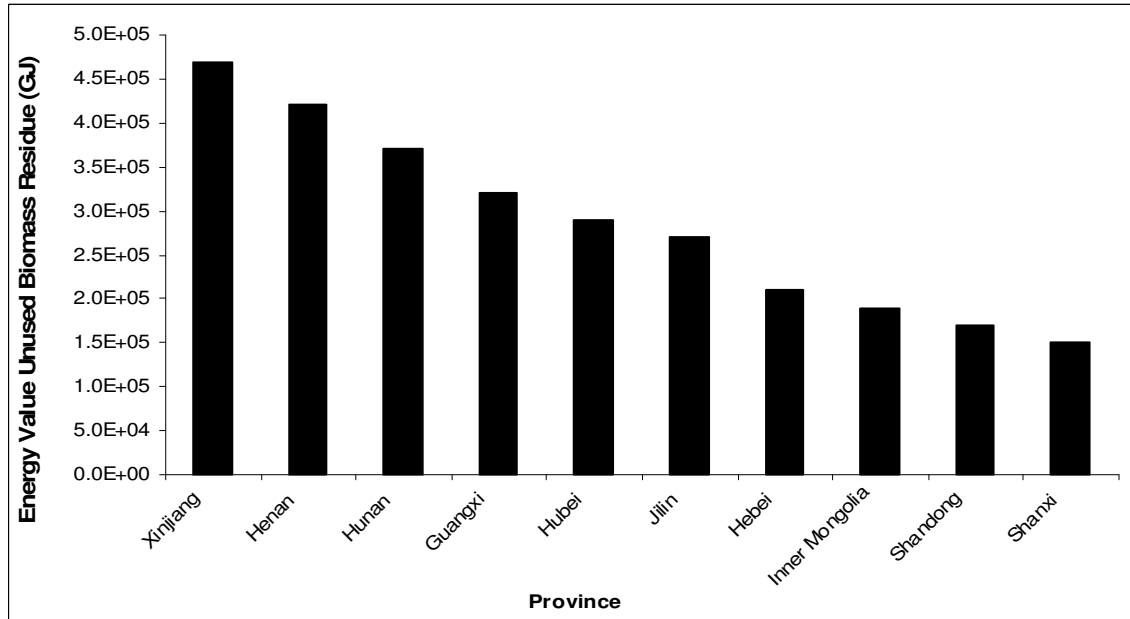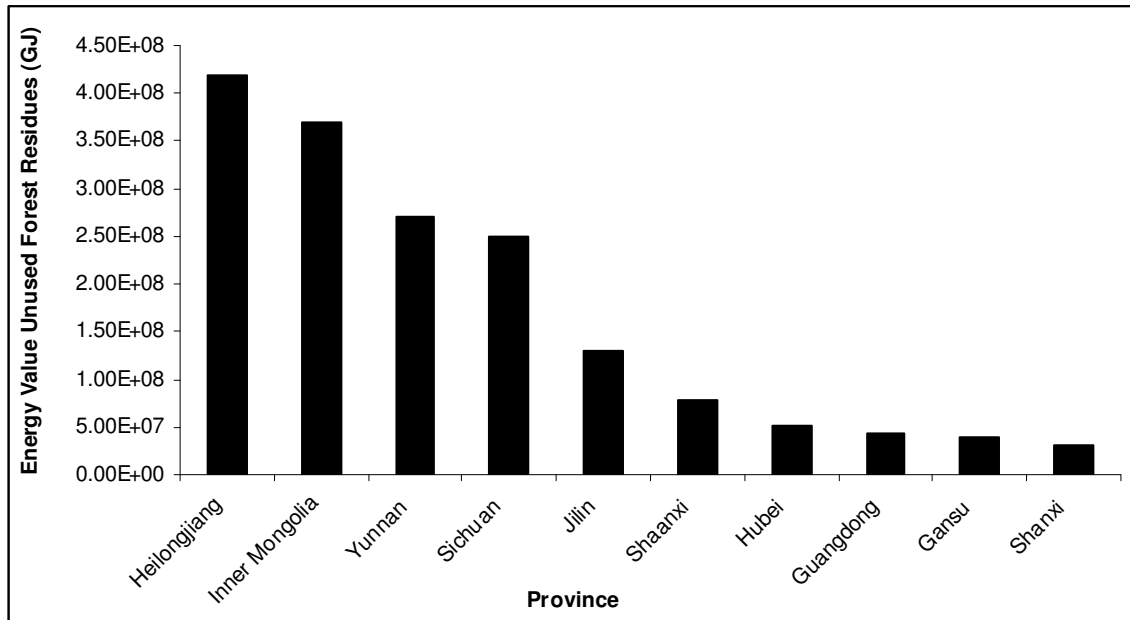

Figure III-3. Total annual energy value (GJ) of unused forest residues in the ten provinces in China with the greatest forest resources. The total annual value of unused forest residues in China is 1.6×10^9 GJ. The top ten provinces account for 70% of the biomass residue energy value.

b. Sludges

China, like many countries around the world, is rapidly expanding wastewater treatment, and subsequently sewage sludge quantities are also rapidly increasing. In 2005, wastewater treatment plants in China generated 9 million tons of dewatered sludge, and within ten years, the quantity is expected to increase to 27 million tons (He 2007). Nine million tons of dewatered sludge has an energy equivalent of approximately 108 million GJ or approximately 4.1 million tons of coal.

The use of sewage sludge in cement manufacturing in China is likely to become increasingly attractive due to the barriers that exist to other sludge disposal and handling routes. For example, according to a sludge management policy passed by the Chinese Ministry of Construction, sludge tipping at landfills cannot exceed more than 5% of the daily capacity of the landfill (Zhou 2006). Land application is a popular end-use for sewage sludge in countries around the world, since it has the potential to offset commercial fertilizer demand and to enrich the soil. Sludge that is applied to land must comply with strict human and environmental health standards. Thus, sludge that is contaminated with heavy metals from industrial wastewaters is unfit for use in agriculture.

At present, there is at least one example of sewage sludge being used in cement manufacturing in China. In spring 2008, the government in Chongqing entered into an agreement with the Lafarge Cement Manufacturing Company in Chongqing to accept sewage sludge from the largest municipal wastewater treatment plant. In May they will begin operating a temporary facility accepting 40-50 t/d and by August they will be accepting approximately 40,000 t sewage sludge/day.

As discussed earlier, China has a substantial paper manufacturing sector and an inevitable byproduct is paper sludge. According to Chinese government statistics, the paper industry produces an annual volume 16 M tons of waste and approximately 2.5 M tons are unused (National Bureau of Statistics of P.R. China 2007). Further investigation is necessary to determine the geographic location and dispersion of these sludges in order to assess the feasibility of using them in cement manufacturing.

4. Miscellaneous Waste Fuels

a. Automobile Shredder Residue (ASR)

Automobile production and ownership is rapidly increasing in China. In 2005 there were 35 million vehicles in use in China, and 2.1 million end-of-life vehicles (ELV); it is predicted that by 2010 there will be 55 million vehicles and 3.3 million ELVs, and by 2020, 100 million vehicles and 8 million ELVs (Chen 2006). Recognizing the importance of environmentally sound vehicle disassembly, recycling, and recovery measures, the National Development and Reform Commission, the Ministry of Science and Technology, and the State Environmental Protection Agency issued the Motor Vehicle Product Recovery Technology Policy in February 2006. The policy mandates that by 2010, car manufacturers must take responsibility for dismantling ELVs or designate an authorized entity to do so. The reuse and recovery rates for commercial vehicles are to achieve 85% and 80% by average weight, respectively by 2010; reuse and recovery rates for passenger vehicles are to achieve 80% and 75% by average weight, respectively by 2010 (Chen 2006). Ultimately, recoverability rates of all vehicles are to reach 95% by 2017 and energy recovery is expected to account for 5% of this goal (Chen 2006). Chinese cement manufacturers can play an important role in helping to attain the ASR energy recovery goal. As of 2006, there were 365 certified automobile disassemblers throughout the country (Beck 2006). Further investigation of their capacity and location with respect to cement manufacturers is the necessary next step in assessing the viability, costs and benefits of using ASR in cement kilns in China.

b. Textiles

According to Chinese government statistics, the textile industry in China produces an annual volume of nearly 7 M tons of solid waste, approximately 0.5 M tons of which are unused (National Bureau of Statistics of P.R. China 2007). Further investigation is necessary to determine the geographic location and dispersion of these sludges if the unused waste could be successfully utilized by cement kilns.

5. Discussion and Conclusions

The emphasis of this report has been on the use of alternative fuels in cement manufacturing; the purpose being to decrease reliance on fossil fuels, and reduce the carbon footprint and global warming impact of the industry. Kiln technology also influences the carbon intensity of cement manufacturing because of differences in the thermal efficiencies of different kiln types. Thus this report would be incomplete without a discussion of the technology improvements which have potential to contribute to fuel savings and carbon emissions reductions in China's cement industry.

As was discussed in Section I of this report, there are significant differences in the energy efficiencies of different kiln types. The best available kiln technology, a rotary preheater/precalciner kiln, requires 2.9-3.2 GJ/ton clinker, whereas an ordinary shaft kiln requires 3.7-6.6 GJ/ton clinker (Price 2007; Karstensen 2008). Rotary kilns are the most common kiln type in industrialized countries, but China still relies heavily on vertical shaft kilns (van Oss 2002). As of 2007, outdated kiln technologies including VSKs and wet process kilns accounted for approximately 45% of China's cement production, down from about 75% of cement production in 2001 (Price 2007; Cui April 2008).

China's heavy use of VSKs renders the average energy demand for cement production substantially higher than the world average. Outside of China, the average energy consumption is 2.88 GJ/ton clinker compared to 3.55 GJ/ton clinker within China (Cui April 2008). This higher average energy consumption in China entails an additional 0.08 tons CO_2/ton clinker produced or nearly 99 M tons CO_2/year. A simple comparison of pursuing carbon reductions through kiln technology improvements versus the use of alternative fuels provides insight into the potential impacts of each alternative. Assuming the best (but unlikely) case, that all unused agricultural biomass residues were used in cement kilns, the result would entail a carbon offset of 0.02 M tons CO_2/year. This is three orders of magnitude less than the potential offsets from replacing inefficient technology to bring China's kiln energy consumption in line with the world average. On the other hand, using all unused forest residues in cement kilns (again, an unlikely scenario,) would avoid 154 M tons CO_2/year.

The message from this simple analysis is that the replacement of obsolete kiln technologies and the use of alternative fuels are both important components of improving the environmental and economic sustainability of cement production in China. Each of these alternatives has associated costs and benefits that may make it more or less practical at a given time for a given cement plant. For example, replacing kilns is technically and institutionally straightforward but may be economically challenging; utilizing alternative fuels may be desirable but impractical due to the geographical distribution of the waste fuels. For alternative fuels that require state of the art emission controls to prevent the release of heavy metals and/or dioxins during incineration, the replacement of VSKs may be a pre-requisite for them to be safely utilized by cement plants. Because of these case-sensitive variables, projects undertaken by cement plants to improve their energy efficiency and carbon intensity should avoid prescriptive decision making. Rather, cement plants and all relevant stakeholders should favor exploratory and knowledge-

driven planning processes to arrive at project designs that are both high impact and feasible.

Literature Cited

Asian Development Bank (2006). Small Scale Clean Development Mechanism Project Handbook. Philippines, Asian Development Bank,.

Bech, C. (2006). "GCHI-a leader in waste derived fuel management." Cement Industry Technical Conference, 2006. Conference Record. IEEE: 11.

Beck, M. (2006). Car and e-scrap recycling. Recycling International: 20-22.

Boughton, B., Horvath, A. (2004). "Environmental assessment of used oil management methods." Environ Sci Technol **38**(2): 353-359.

Boughton, B., Horvath, A. (2006). "Environmental assessment of shredder residue management." Resources, Conservation and Recycling **47**: 1-25.

CEMBUREAU (1997). Alternative Fuels in Cement Manufacturing: Technical and Environmental Review. Brussels, The European Cement Association: 24.

CEMBUREAU (1999). Environmental Benefits of Using Alternative Fuels in Cement Production. Brussels, The European Cement Association: 25.

Cement Sustainability Initiative (2005). Guidelines for the Selection and Use of Fuels and Raw Materials in the Cement Manufacturing Process, World Business Council for Sustainable Development: 38.

Chen, M. (2006). "Sustainable recycling of automotive products in China: Technology and regulation." JOM Journal of the Minerals, Metals and Materials Society **58**(8): 23-26.

China Daily (November 15, 2007). Cement manufacturing industry gets new guidelines. China Daily. Beijing.

Christen, K. (March 22, 2006). "Expanding automotive recycling to include plastics." Technology News Retrieved February 22, 2008, from http://pubs.acs.org/subscribe/journals/esthag-w/2006/mar/tech/kc_autorecycling.html.

Corti, A. and L. Lombardi (2004). "End life tyres: Alternative final disposal processes compared by LCA." Energy **29**(12-15): 2089-2108.

Cui, Y. (April 2008). Outlook of cement industry in China. 10th Asia Cement Trade Conference, Singapore.

Demirbas, A. (2003). "Sustainable cofiring of biomass with coal." Energy Conversion and Management **44**(9): 1465-1479.

European Commission (EC) (2004). Sustainability Impact Assessment (SIA) Methodology: Towards an upgrade in 2004. SIA Methodology: Consultation Paper. D.-G. f. Trade. Brussels, EC

Fytili, D., Zabaniotou, A. (2006). "Utilization of sewage sludge in EU application of old and new methods - a review." Renewable and Sustainable Energy Review **12**(1): 116-140.

Gendebien, A., Leavens, A., Blackmore, K. , Godley, A. , Lewin, K. , Whiting, K., Davis, R., Giegrich, J., Fehrenbach, H., Gromke, U., del Bufalo, N., Hogg, D. (2003). Refuse Derived Fuel, Current Practice and Perspectives: Final Report, European Commission - Directorate General Environment**:** 229.

Genon, G., Brizio, E. (2008). "Perspectives and limits for cement kilns as a destination for RDF." Waste Management **In Press, Corrected Proof**.

Grasim Industries Ltd-Cement Division South (2005). Clean Development Mechanism Project Design Document Form, UNFCCC.

GTZ and Holcim (2006). Guidelines on Co-Processing Waste Materials in Cement Production. The GTZ-Holcim Public Private Parternship, GTZ and Holcim Group Support Ltd.**:** 135.

Hammett, A., Youngs, R., Sun, X., Chandra, M. (2001). "Non-wood fiber as an alternative to wood fiber in China's pulp and paper industry." Holzforschung **55**(2): 219-224.

Harrell, M., Manager of Alternative Fuel and Resource Recovery, personal communication with A. Murray (March 4, 2008). Use of alternative fuels by Ash Grove cement company, Ash Grove Cement Company, Kansas.

He, P., Lü, F., Zhang, H., Shao, L. M., Lee, D. J. (2007). "Sewage sludge in China: challenges toward a sustainable future." In: LeBlanc, Ronald J.

ICF Consulting (2005). Determination of the Impact of Waste Management Activities on Greenhouse Gas Emissions: 2005 Update. Toronto, Environment Canada and Natural Resources Canada**:** 163.

ICF Consulting (2006). Life-Cycle Greenhouse Gas Emission Factors for Scrap Tires, US Environmental Protection Agency**:** 8.

IEA (2007). Energy Balances of Non-OECD Countries: Beyond 2020 Documentation, International Energy Agency**:** 77.

IEA (2007). Tracking industrial energy efficiency and CO2 emissions. Paris, International Energy Agency.

IPCC (1996). Guidelines for National Greenhouse Gas Inventories, Vol III, Intergovernmental Panel on Climate Change.

IPCC (2006). Guidelines for National Greenhouse Gas Inventories, Vol 5 Waste, Intergovernmental Panel on Climate Change.

IPCC (2006). IPCC Emissions Factor Database, Intergovenmental Panal on Climate Change.

IPCC (2007). Climate Change 2007: Synthesis Report. Valencia, Spain, Intergovernmental Panel on Climate Change**:** 52.

Jenkins, B. M., L. L. Baxter, et al. (1998). "Combustion properties of biomass." Fuel Processing Technology **54**(1-3): 17-46.

Jorapur, R., Rajvanshi, A. (1997). "Sugarcane leaf-bagasse gasifiers for industrial heating applications." Biomass and Bioenergy **13**(3): 141-146.

Kaantee, U., R. Zevenhoven, et al. (2004). "Cement manufacturing using alternative fuels and the advantages of process modelling." Fuel Processing Technology **85**(4): 293-301.

Kaplan, E., Nedder, N (2001). Petroleum coke utilization for cement kiln firing. Cement Industry Technical Conference, IEEE-IAS/PCA 2001.

Karstensen, K. (2008). "Formation, release and control of dioxins in cement kilns." Chemosphere **70**: 543-560.

Karstensen, K., Kinh, N., Thang, L., Viet, P., Tuan, N., Toi, D., Hung, N., Quan, T., Hanh, L., Thang, D. (2006). "Environmentally sound destruction of obsolete pesticides in developing countries using cement kilns." Environ Sci Technol **9**: 577-586.

Lafarge. (2007). "Case Study, Environment: Retzei - Using plastic as alternative fuel." March 2008, from http://www.lafarge.com/wps/portal/2_4_4_1-EnDet?WCM_GLOBAL_CONTEXT=/wps/wcm/connect/Lafarge.com/AllCS/Env/NR/CP1610621357/CSEN.

Lafarge Malayan Cement Bhd (2005). Monitoring Report for Replacement of Fossil Fuel By Palm Kernel Shell Biomass in the Production of Portland Cement. Selangor, Malaysia**:** 35.

Li, J., Zhuang, X., DeLaquil, P., Larson, E. (2001). "Biomass energy in China and its potential." Energy for Sustainable Development **5**(4): 66-81.

Liao, C., Yanyongjie, Wu, C., Huang, H. (2004). "Study on the distribution and quantity of biomass residues resource in China." Biomass and Bioenergy **27**(2): 111-117.

Life Cycle Associates (2007). BEACCON model (http://www.lifecycleassociates.com/).

Mani, S., L. G. Tabil, et al. (2004). "Grinding performance and physical properties of wheat and barley straws, corn stover and switchgrass." Biomass and Bioenergy **27**(4): 339-352.

Mansaray, K., Ghaly, A. (1997). "Physical and Thermochemical Properties of Rice Husk." Energy Sources, Part A: Recovery, Utilization, and Environmental Effects **19**(9): 989-1004.

Maxham, J. (1992). Conversion of paper mill sludge into papermaking pulp and filler products, Division of Pollution Prevention and Environmental Assistance, North Carolina Department of Environment and Natural Resoures**:** 14.

McGray, S., Process Engineer, personal communication with A. Murray. (February 18, 2008). Use of tires as alternative fuel in cement manufacturing, California Portland Cement Company, Colton, CA.

McIlveen-Wright, D. R., Y. Huang, et al. (2007). "A technical and environmental analysis of co-combustion of coal and biomass in fluidised bed technologies." Fuel **86**(14): 2032-2042.

Metz, B., Davidson, O., Bosch, P., Dave, R., Meyers, L. (eds) (2007). Climate Change 2007: Mitigation of Climate Change. Contribution of Working Group III to the Fourth Assessment Report of the IPCC. New York, NY, Intergovernmental Panel on Climate Change.

Mirabile, D., M. I. Pistelli, et al. (2002). "Thermal valorisation of automobile shredder residue: injection in blast furnace." Waste Management **22**(8): 841-851.

Mokrzycki, E. and A. Uliasz- Bochenczyk (2003). "Alternative fuels for the cement industry." Applied Energy **74**(1-2): 95-100.

Mokrzycki, E., A. Uliasz-Bochenczyk, et al. (2003). "Use of alternative fuels in the Polish cement industry." Applied Energy **74**(1-2): 101-111.

Murray, A., Horvath, A., Nelson, K. (2008). "Hybrid life-cycle environmental and sludge cost inventory of sewage sludge treatment and end-use scenarios: A case study from China." Environ Sci Technol **DOI: 10.1021/es702256w**.

National Bureau of Statistics of P.R. China (2007). China Statistical Yearbook, China Statistics Press.

Peltier, R. (2003). "Mercury removal standards are coming. Where's the technology? (Cover story)." Power **147**(4): 40.

Portland Cement Association (2006). Report on Sustainable Manufacturing.

Price, L., Galitsky, C. (2007). Opportunities for improving energy efficiency and increasing economic output in Chinese cement kilns. ACEEE Summer Study on Energy Efficiency in Industry.

Realff, M., Lemieux, P., Lucero, S., Mulholland, J., Smith P (2005). Characterization of transient puff emissions from the burning of carpet waste charges in a rotary kiln combustor. Cement Industry Technical Conference, 2005. Conference Record.

Reijnders, L. (2007). "The cement industry as a scavenger in industrial ecology and the management of hazardous substances." Journal of Industrial Ecology **11**(3): 15-25.

Resource Management Branch (1996). Composting Factsheet. Abbotsford, BC, Canada, British Columbia Ministry of Agriculture Food and Fisheries.

Ryu, C., A. N. Phan, et al. (2007). "Combustion of textile residues in a packed bed." Experimental Thermal and Fluid Science **31**(8): 887-895.

Saft, R. (2007). "Life cycle assessment of a pyrolysis/gasification plant for hazardous paint waste." The International Journal of Life Cycle Assessment **12**(4): 230-238.

Schmidthals, H. and H. Schmidthals (2003). The pre-combustion chamber for secondary fuels development status of a new technology. Cement Industry Technical Conference, 2003. Conference Record. IEEE-IAS/PCA 2003.

Seyler, C., Hellweg, S., Monteil, M., Hungerbühler, K. (2005). "Life cycle inventory for use of waste solvent as fuel substitute in the cement industry-a multi-input allocation model " The International Journal of Life Cycle Assessment **10**(2): 120-130.

Seyler, C., T. B. Hofstetter, et al. (2005). "Life cycle inventory for thermal treatment of waste solvent from chemical industry: a multi-input allocation model." Journal of Cleaner Production **13**(13-14): 1211-1224.

Siddique, R., J. Khatib, et al. "Use of recycled plastic in concrete: A review." Waste Management **In Press, Corrected Proof**.

Subramanian, P. M. (2000). "Plastics recycling and waste management in the US." Resources, Conservation and Recycling **28**(3-4): 253-263.

UNEP Chemicals (2005). Standardized Toolkit for Identification and Quantification of Dioxin and Furan Releases. Geneva, Switzerland, United Nations Environment Programme Chemicals**:** 194.

UNEP Chemicals (2005). Toolkit for Identification and Quantification of Mercury Releases. Geneva, Switzerland, United Nations Environment Programme Chemicals**:** 282.

US EPA. (2007). "Automotive Parts."   Retrieved February 22, 2008, from http://www.epa.gov/garbage/auto.htm.

Vaajasaari, K., M. Kulovaara, et al. (2004). "Hazardous properties of paint residues from the furniture industry." Journal of Hazardous Materials **106**(2-3): 71-79.

Vaccaro, M. and M. Vaccaro (2006). Burning alternative fuels in rotary cement kilns Burning alternative fuels in rotary cement kilns. Cement Industry Technical Conference, 2006. Conference Record. IEEE.

Vallet, F., Resource Recovery Manager, personal communication: Murray, A. (January 26, 2007). Lafarge China cement manufacturing overview. Lafarge Shui On Cement, Chongqing, Sichuan Province, China.

van Oss, H., Padovani, A. (2002). "Cement manufacture and the environment part I: chemistry and technology." Journal of Industrial Ecology **6**(1): 89-105.

WBCSD (2002). Toward a Sustainable Cement Industry: Environment, Health, and Safety Performance Improvement, World Business Council for Sustainable Development**:** 58.

WBCSD (2006). Formation and Relsease of POPs in the Cement Industry. Cement Sustainability Initiative, World Business Council for Sustainable Development**:** 200.

Ye, T. H., J. Azevedo, et al. (2004). "Co-combustion of pulverized coal, pine shells, and textile wastes in a propane-fired furnace: Measurements and predictions." Combustion Science and Technology **176**(12): 2071-2104.

Zementwerke, V. (2002). Environmental Data of the German Cement Insustry 2001, German Cement Works Association**:** 52.

Zhou, J., Zhang, H., Wang, J.W., Gan, Y.P., Wang, H.C. (2006). Biosolids management and legislation in China. Beijing, Beijing Drainage Group CO., Ltd.**:** 11.

APPENDIX A: Alternative Fuel Characteristics

Table A.1. Overview of key combustion characteristics and typical substitution rates of a variety of alternative fuels used for cement manufacturing. Blanks left where data were not available.

fuel	substitution rate (%)	lower heat value (GJ/DT)	water content (%)	ash content (%)	C content (% by dry wt)	C EF (tonsC-eq/ton)	ΔCO_2 (ton)/ton coal replacement	associated emissions	data source
				Agricultural biomass					
rice husks	35	13.2-16.2	10	20.6	38.8	0.35	0.0	Cl	(Mansaray 1997; Jenkins, Baxter et al. 1998; Demirbas 2003)
wheat straw	20	15.8; 18.2	14.2; 7.3; 12	4.5; 3-5; 8.9	44.9; 48.8	0.42	0.2		(Mansaray 1997; Jenkins, Baxter et al. 1998; Demirbas 2003; Asian Development Bank 2006; McIlveen-Wright 2007)
corn stover	20	15.4	9.41; 35; 11	7.46; 3.25	42.5	0.28	-0.6		(Demirbas 2003; Mani, Tabil et al. 2004; Asian Development Bank 2006)
sugarcane leaves	20	15.8	<15	7.7	39.8	0.34	-0.1		
sugarcane (bagasse)	20	14.4; 15.6; 19.4	10-15	4.2	44.1	0.39	0.4		(Li 2001; Demirbas 2003; Asian Development

									Bank 2006)
rapeseed stems	20	16.4	12.6	5.9	45.2	0.39	0.1		
hazelnut shells	20	17.5	9.2	3.5	52.9	0.48	0.4		
palm nut shells	20	11.9	10			0.36	0.7		
Non-Agricultural biomass									
dewatered sewage sludge	20	10.5 - 29	75	21.8	53.92; 30	0.21-0.39	0.04	heavy metals	(Fytili 2006; IPCC 2006; McIlveen-Wright 2007)
heat dried sewage sludge			10				-0.37	heavy metals	(Fytili 2006; IPCC 2006; McIlveen-Wright 2007)
paper sludge	20	8.5	70	26		0.2	1.36	Cl	(Maxham 1992; European Commission (EC) 2004)
paper	20	12.5-22		8.33	47.99	0.42	-0.15	Cl	(Jenkins, Baxter et al. 1998; European Commission (EC) 2004)
sawdust	20	16.5	20	2.6	46.9	0.38	0.14	Cl (if from treated wood)	(Resource Management Branch 1996; Demirbas 2003)
waste wood	20	15.5; 17.4	33.3	0.9	50	0.33; 0.49	1.32	Cl, toxics if treated or painted	(Bhattacharya, Abdul Salam et al. 2000; Li 2001; IPCC 2006; McIlveen-Wright 2007)
animal waste (bone		16-17; 19	15		34	0.29	-0.71		(Bhattacharya,

meal, animal fat)									Abdul Salam et al. 2000; Zementwerke 2002; European Commission (EC) 2004
Chemical and hazardous waste									
spent solvent		Range: 0-40 Avg.: 21-25	10.3; 16.5		47.7	0.4	-0.89	dioxins	(Zementwerke 2002; Seyler 2005; Seyler, Hofstetter et al. 2005)
paint residues		16.3	9	34	41-51	0.42	0.21		(Vaajasaari, Kulovaara et al. 2004; Saft 2007)
hazardous waste (misc)					50	0.14		dioxins, heavy metals	(IPCC 2006)
obsolete pesticides	57	33.3						NO$_x$	(Karstensen 2006)
Petroleum-based waste									
tires	< 20%	27.8; 37.1	0.3			0.56	-0.83	NO$_x$, SO$_2$, CO	(ICF Consulting 2006)
polyethylene		46	2.1	27.4	71	0.7	-1.03	Cl	(Subramanian 2000; European Commission (EC) 2004)
polypropylene		46	2.1	27.4	71	0.7	-1.03	Cl	(Subramanian 2000; European Commission (EC) 2004)
polystyrene		41	2.1	27.4	71	0.7	-0.85	Cl	(Subramanian

									2000; European Commission (EC) 2004)
waste oils		21.6	5		46	0.44	-0.53	Zn, Cd, Cu, Pb	(Mokrzycki, Uliasz-Bochenczyk et al. 2003; Boughton 2004; IPCC 2006)
petroleum coke (petcoke)		18.9; 33.7	0.4		78.24% C	0.5-0.9	0.21	SO_2, NO_x, CO	(Kaplan 2001; Mokrzycki, Uliasz-Bochenczyk et al. 2003; Prisciandaro, Mazziotti et al. 2003; Kaantee, Zevenhoven et al. 2004; IPCC 2006)
Miscellaneous waste									
polypropylene carpet residues		28.1	0.2	21.2	56.9	0.57	-0.54	Cl, Sb, Cr, Zn	(Realff 2005; Boughton 2007)
nylon carpet residues		17.2	0.9	25.4	42.2	0.42	-0.15	Cl, Sb, Cr, Zn, NO_x	(Realff 2005; Boughton 2007)
textiles	30	16.3	5.8	1.2	44.6	0.42	0.11	Sb, Cr, Zn	(Ye, Azevedo et al. 2004)
automotive shredder residues	2	16.5	2.2	36.2	46.2	0.44	0.10	Cl, heavy metals	(Mirabile, Pistelli et al. 2002)
demolition and commercial waste		25	18.8	20.6					(European Commission

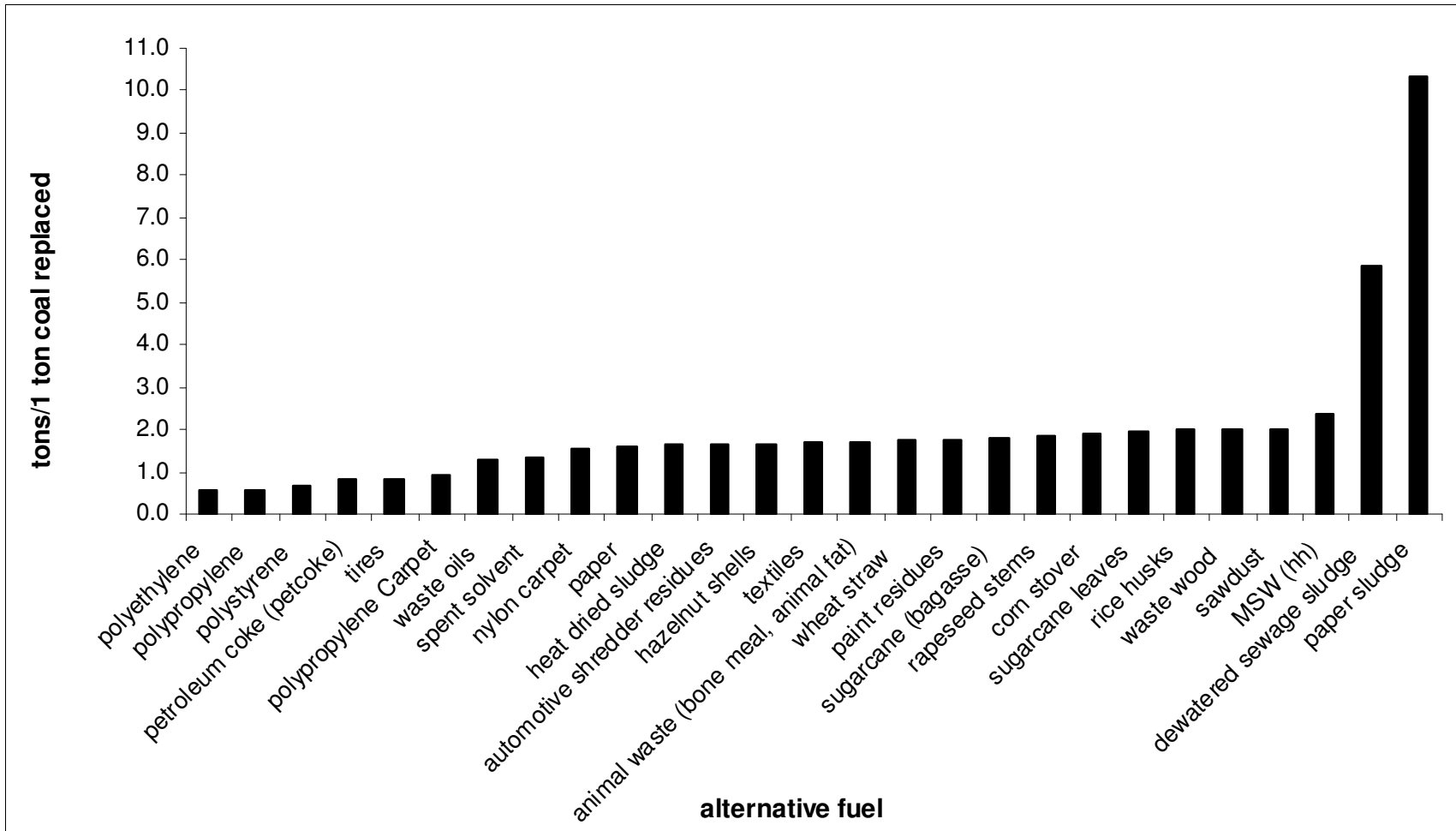|								
								(EC) 2004)
landfill gas		19.7	-			0.3	-1.02		(Asian Development Bank 2006)
MSW (hh)		12-16	10-35		40	0.26-0.36	-0.01	Cl, heavy metals, NO$_x$	(European Commission (EC) 2004; IPCC 2006)

Figure A.2. Tons of alternative fuel required to replace 1 ton of coal. Values are dependent on material's energy and water content. Substitution assumes coal has a LHV of 26.3 GJ/ton.

APPENDIX B: China Biomass Production and Availability

Table B.1. Provincial-level breakdown of the energy value of biomass crop residues in China. Data for the ten provinces with the greatest potential energy value of unused residues, and the total energy value of residues in China are provided. Original data for residue yields from Liao et al. (reproduced in Table B.2.); see Table A.1. for the LHV of each crop.

province	rice straw (GJ)	soybean stems & leaves (GJ)	sorghum wheat (GJ)	wheat straw (GJ)	sugarcane leaves (GJ)	sunflower stalks (GJ)	rapeseed stems (GJ)	corn stalks (GJ)	cotton stalks (GJ)	hemp stems (GJ)	total energy value (GJ)	energy value of unused residues (GJ)	coal eq. (tons)
Xinjiang	4.7×10^6	2.6×10^6	1.0×10^6	9.0×10^7	0	6.0×10^6	4.0×10^6	8.1×10^7	6.1×10^7	0	2.5×10^8	4.7×10^5	1.8×10^4
Henan	3.1×10^7	2.7×10^7	5.8×10^4	4.1×10^8	2.5×10^5	1.2×10^5	1.1×10^7	3.2×10^8	3.2×10^7	3.2×10^6	8.4×10^8	4.2×10^5	1.6×10^4
Hunan	1.9×10^8	7.7×10^6	3.8×10^5	5.1×10^6	2.9×10^6	1.5×10^4	3.1×10^7	2.4×10^7	8.4×10^6	1.7×10^6	2.8×10^8	3.7×10^5	1.4×10^4
Guangxi	1.1×10^8	2.1×10^7	1.0×10^5	6.9×10^5	5.7×10^7	0	3.7×10^6	4.6×10^7	3.9×10^4	7.2×10^5	2.2×10^8	3.2×10^5	1.2×10^4
Hubei	1.4×10^8	9.7×10^6	2.2×10^5	8.1×10^7	1.7×10^6	1.5×10^5	5.1×10^7	5.5×10^7	1.4×10^7	3.1×10^6	3.5×10^8	2.9×10^5	1.1×10^4
Jilin	3.2×10^7	1.8×10^7	5.3×10^6	2.1×10^6	0	4.3×10^6	0	5.7×10^8	0	1.6×10^4	6.3×10^8	2.7×10^5	1.0×10^4
Hebei	8.2×10^6	1.8×10^7	3.2×10^6	2.5×10^8	0	2.2×10^6	1.4×10^6	3.5×10^8	1.2×10^7	5.9×10^5	6.4×10^8	2.1×10^5	8.0×10^3
Inner Mongolia	5.0×10^6	2.2×10^7	6.7×10^6	5.6×10^7	0	1.7×10^7	4.6×10^6	2.5×10^8	1.0×10^5	1.2×10^5	3.6×10^8	1.9×10^5	7.1×10^3
Shandong	1.2×10^7	3.2×10^7	2.6×10^5	4.0×10^8	0	2.6×10^4	1.2×10^6	4.6×10^8	1.8×10^7	4.3×10^5	9.2×10^8	1.7×10^5	6.4×10^3
Shanxi	3.3×10^5	8.3×10^6	5.4×10^6	6.4×10^7	0	6.0×10^6	4.3×10^5	1.4×10^8	2.4×10^6	1.9×10^4	2.3×10^8	1.5×10^5	5.7×10^3
China Total	1.6×10^9	3.5×10^8	5.8×10^7	2.0×10^9	1.1×10^8	4.2×10^7	2.6×10^8	3.8×10^9	1.9×10^8	1.9×10^7	8.4×10^9	4.1×10^6	1.6×10^5

Table B.2. Provincial-level breakdown of biomass crop residue yields in China. Data are for the ten provinces with the greatest quantity of unused residues. Data are reproduced from Liao et al. 2004.

province	rice straw (1000 t)	soybean stems & leaves (1000 t)	sorghum wheat (1000 t)	wheat straw (1000 t)	sugarcane leaves (1000 t)	sunflower stalks (1000 t)	rapeseed stems (1000 t)	corn stalks (1000 t)	cotton stalks (1000 t)	hemp stems (1000 t)	residue yield (1000 t)	unused residue (1000 t)
Xinjiang	351	164	69	6,237		416	246	5,496	4,200		17,179	32,273
Henan	2,303	1,682	4	28,324	15.9	8.2	677	21,926	2,185	192	57,317	29,140
Hunan	14,609	562	26	351	188	1	1,892	1,642	577	106	19,954	25,123
Guangxi	8,042	484	7	48	3,582		226	3,124	2.7	44	15,560	22,128
Hubei	10,175	611	15	5,591	110	10	3,095	3,734	975	186	24,502	20,145
Jilin	2,402	1,107	367	145		296		38,494		1	42,812	18,481
Hebei	618	1,140	219	17,124		150	83	23,744	811	36	43,925	14,544
Inner Mongolia	376	1,406	461	3,862		1,189	281	16,796	7	7	24,385	12,951
Shandong	865	2,052	18	27,655		1.76	72.3	31,072	1,238	26	63,000	11,722
Shanxi	25	525	374	4,384		414	26	9,522	168	1.2	15,439	10,275
China Total	117,613	22,378	4,005	138,635	6,739	2,916	15,752	255,851	13,495	1,180	578,564	285,674

Table B.3. Provincial-level breakdown of the energy value of forest biomass residues in China. Data for the ten provinces with the greatest quantity of unused residue in terms of energy, and the total residue energy value for China are provided. Original data for residue yields from Liao et al (reproduced in Table B.3.). Data were converted assuming a LHV of wood biomass of 15.5 GJ/t.

province	timber stands (GJ)	protected forests (GJ)	firewood forests (GJ)	special use forests (GJ)	economic forests (GJ)	sparse forest (GJ)	shrubs (GJ)	orchard (GJ)	total energy value (GJ)	energy value of unused residues (GJ)	coal eq. (tons)
Heilongjiang	4.1×10^8	5.2×10^6	1.3×10^7	2.2×10^6	1.9×10^5	2.5×10^7	1.1×10^6	1.7×10^5	4.6×10^8	4.2×10^8	1.6×10^7
Inner Mongolia	3.4×10^8	4.6×10^6	5.9×10^6	1.9×10^6	2.6×10^6	1.7×10^7	2.9×10^7	2.2×10^5	4.0×10^8	3.7×10^8	1.4×10^7
Yunnan	1.8×10^8	1.9×10^7	2.2×10^7	1.7×10^6	1.7×10^6	3.9×10^7	6.4×10^7	5.7×10^5	3.2×10^8	2.7×10^8	1.0×10^7
Sichuan	1.8×10^8	3.9×10^7	7.4×10^5	4.5×10^5	2.0×10^6	4.2×10^7	1.1×10^8	6.9×10^5	3.8×10^8	2.5×10^8	9.5×10^6
Jilin	1.5×10^8	9.5×10^6	8.8×10^5	8.2×10^5	1.2×10^5	6.4×10^6	8.1×10^6	2.9×10^5	1.7×10^8	1.3×10^8	4.9×10^6
Shaanxi	2.4×10^7	2.5×10^5	9.5×10^5	1.2×10^8	4.1×10^6	1.6×10^7	1.9×10^6	1.4×10^8	5.9×10^7	7.9×10^7	3.0×10^6
Hubei	2.4×10^7	7.8×10^4	1.5×10^6	9.9×10^7	7.1×10^6	1.4×10^7	6.7×10^5	1.2×10^8	7.1×10^7	5.1×10^7	1.9×10^6
Guangdong	1.1×10^8	1.7×10^6	1.3×10^7	6.2×10^4	1.5×10^6	1.3×10^7	5.7×10^6	2.7×10^6	1.4×10^8	4.4×10^7	1.7×10^6
Gansu	1.3×10^6	3.9×10^5	2.3×10^5	4.0×10^7	5.3×10^6	2.0×10^7	8.7×10^5	6.7×10^7	2.7×10^7	4.0×10^7	1.5×10^6
Shanxi	2.1×10^7	1.7×10^6	2.5×10^5	3.1×10^4	3.1×10^5	7.4×10^6	1.2×10^7	8.7×10^5	4.3×10^7	3.1×10^7	1.2×10^6
China Total	2.3×10^9	1.7×10^8	2.6×10^8	9.1×10^6	3.9×10^7	2.8×10^8	4.1×10^8	2.5×10^7	3.5×10^9	1.6×10^9	6.1×10^7

Table B.4. Provincial-level breakdown of forest residue yields in China. Data are for the ten provinces with the greatest quantity of unused residues. Data are reproduced from Liao et al. 2004.

province	timber stands (1000 t)	protected forests (1000 t)	firewood forests (1000 t)	special use forests (1000 t)	economic forests (1000 t)	sparse forest (1000 t)	shrubs (1000 t)	orchard (1000 t)	residue yield (1000 t)	unused residue (1000 t)
Heilongjiang	335	863	143	12	27,815	1,587	72	11	29,485	26,939
Inner Mongolia	298	378	126	168	23,044	1,082	1,909	14	26,049	23,806
Yunnan	1,202	1,385	109	111	14,133	2,564	4,141	37	20,875	17,359
Sichuan	2,537	48	29	130	14,537	2,719	7,324	45	24,625	16,203
Jilin	612	57	53	8	10,247	414	520	19	11,200	8,380
Shaanxi	890	1,559	16	61	7,515	265	1,023	125	8,927	5,119
Hubei	290	1,529	5	96	6,419	459	918	43	7,839	3,278
Guangdong	112	810	4	98	7,850	828	369	173	9,220	2,817
Gansu	590	81	25	15	2,602	343	1,311	56	4,312	2,585
Shanxi	108	16	2	20	1,509	474	739	56	2,778	1,977
China Total	10,918	16,664	584	2,577	180,874	18,409	26,373	1,600	227,256	103,520

Literature Cited in Tables A.1 – B.4

Asian Development Bank (2006). Small Scale Clean Development Mechanism Project Handbook. Philippines, Asian Development Bank,.

Bech, C. (2006). "GCHI-a leader in waste derived fuel management." Cement Industry Technical Conference, 2006. Conference Record. IEEE: 11.

Beck, M. (2006). Car and e-scrap recycling. Recycling International: 20-22.

Bhattacharya, S. C., P. Abdul Salam, et al. (2000). "Emissions from biomass energy use in some selected Asian countries." Energy **25**(2): 169-188.

Boughton, B. (2007). "Evaluation of shredder residue as cement manufacturing feedstock." Resources, Conservation and Recycling **51**(3): 621-642.

Boughton, B., Horvath, A. (2004). "Environmental assessment of used oil management methods." Environ Sci Technol **38**(2): 353-359.

Boughton, B., Horvath, A. (2006). "Environmental assessment of shredder residue management." Resources, Conservation and Recycling **47**: 1-25.

CEMBUREAU (1997). Alternative Fuels in Cement Manufacturing: Technical and Environmental Review. Brussels, The European Cement Association**: 24.

CEMBUREAU (1999). Environmental Benefits of Using Alternative Fuels in Cement Production. Brussels, The European Cement Association**: 25.

Cement Sustainability Initiative (2005). Guidelines for the Selection and Use of Fuels and Raw Materials in the Cement Manufacturing Process, World Business Council for Sustainable Development**: 38.

Chen, M. (2006). "Sustainable recycling of automotive products in China: Technology and regulation." JOM Journal of the Minerals, Metals and Materials Society **58**(8): 23-26.

Christen, K. (March 22, 2006). "Expanding automotive recycling to include plastics." Technology News Retrieved February 22, 2008, from http://pubs.acs.org/subscribe/journals/esthag-w/2006/mar/tech/kc_autorecycling.html.

Corti, A. and L. Lombardi (2004). "End life tyres: Alternative final disposal processes compared by LCA." Energy **29**(12-15): 2089-2108.

Cui, Y. (April 2008). Outlook of cement industry in China. 10th Asia Cement Trade Conference, Singapore.

Demirbas, A. (2003). "Sustainable cofiring of biomass with coal." Energy Conversion and Management **44**(9): 1465-1479.

European Commission (EC) (2004). Sustainability Impact Assessment (SIA) Methodology: Towards an upgrade in 2004. SIA Methodology: Consultation Paper. D.-G. f. Trade. Brussels, EC

Fytili, D., Zabaniotou, A. (2006). "Utilization of sewage sludge in EU application of old and new methods - a review." Renewable and Sustainable Energy Review **12**(1): 116-140.

Gabbard, W., Gossman, D. (1990). "Hazardous waste fuels and the cement kilns." ASTM Standardization News: http://gcisolutions.com/HWF&CKS.htm.

Gendebien, A., Leavens, A., Blackmore, K. , Godley, A. , Lewin, K. , Whiting, K., Davis, R., Giegrich, J., Fehrenbach, H., Gromke, U., del Bufalo, N., Hogg, D. (2003). Refuse Derived Fuel, Current Practice and Perspectives: Final Report, European Commission - Directorate General Environment**: 229.

Genon, G., Brizio, E. (2008). "Perspectives and limits for cement kilns as a destination for RDF." Waste Management **In Press, Corrected Proof**.

Grasim Industries Ltd-Cement Division South (2005). Clean Development Mechanism Project Design Document Form, UNFCCC.

GTZ and Holcim (2006). Guidelines on Co-Processing Waste Materials in Cement Production. The GTZ-Holcim Public Private Parternship, GTZ and Holcim Group Support Ltd.**: 135.

Hammett, A., Youngs, R., Sun, X., Chandra, M. (2001). "Non-wood fiber as an alternative to wood fiber in China's pulp and paper industry." Holzforschung **55**(2): 219-224.

Harrell, M., Manager of Alternative Fuel and Resource Recovery, personal communication with A. Murray (March 4, 2008). Use of alternative fuels by Ash Grove cement company, Ash Grove Cement Company, Kansas.

He, P., Lü, F., Zhang, H., Shao, L., Lee, D. (2007). "Sewage Sludge in China: Challenges Toward a Sustainable Future." Water Practice & Technology **2**(04).

Herat, S. (1997). "Protecting the environment from waste disposal: The cement kiln option." Environment Protection Engineering(1): 25-36.

ICF Consulting (2005). Determination of the Impact of Waste Management Activities on Greenhouse Gas Emissions: 2005 Update. Toronto, Environment Canada and Natural Resources Canada**: 163.

ICF Consulting (2006). Life-Cycle Greenhouse Gas Emission Factors for Scrap Tires, US Environmental Protection Agency**: 8.

IEA (2007). Energy Balances of Non-OECD Countries: Beyond 2020 Documentation, International Energy Agency**: 77.

IEA (2007). Tracking industrial energy efficiency and CO2 emissions. Paris, International Energy Agency.

IPCC (1996). Guidelines for National Greenhouse Gas Inventories, Vol III, Intergovernmental Panel on Climate Change.

IPCC (2006). Guidelines for National Greenhouse Gas Inventories, Vol 5 Waste, Intergovernmental Panel on Climate Change.

IPCC (2006). IPCC Emissions Factor Database, Intergovenmental Panal on Climate Change.

IPCC (2007). Climate Change 2007: Synthesis Report. Valencia, Spain, Intergovernmental Panel on Climate Change**: 52.

Jenkins, B. M., L. L. Baxter, et al. (1998). "Combustion properties of biomass." Fuel Processing Technology **54**(1-3): 17-46.

Jorapur, R., Rajvanshi, A. (1997). "Sugarcane leaf-bagasse gasifiers for industrial heating applications." Biomass and Bioenergy **13**(3): 141-146.

Kaantee, U., R. Zevenhoven, et al. (2004). "Cement manufacturing using alternative fuels and the advantages of process modelling." Fuel Processing Technology **85**(4): 293-301.

Kaplan, E., Nedder, N (2001). Petroleum coke utilization for cement kiln firing. Cement Industry Technical Conference, IEEE-IAS/PCA 2001.

Karstensen, K. (2008). "Formation, release and control of dioxins in cement kilns." Chemosphere **70**: 543-560.

Karstensen, K., Kinh, N., Thang, L., Viet, P., Tuan, N., Toi, D., Hung, N., Quan, T., Hanh, L., Thang, D. (2006). "Environmentally sound destruction of obsolete pesticides in developing countries using cement kilns." Environ Sci Technol **9**: 577-586.

Lafarge. (2007). "Case Study, Environment: Retzei - Using plastic as alternative fuel." March 2008, from http://www.lafarge.com/wps/portal/2_4_4_1-EnDet?WCM_GLOBAL_CONTEXT=/wps/wcm/connect/Lafarge.com/AllCS/Env/NR/CP1610621357/CSEN.

Lafarge Malayan Cement Bhd (2005). Monitoring Report for Replacement of Fossil Fuel By Palm Kernel Shell Biomass in the Production of Portland Cement. Selangor, Malaysia**:** 35.

Li, J., Zhuang, X., DeLaquil, P., Larson, E. (2001). "Biomass energy in China and its potential." Energy for Sustainable Development **5**(4): 66-81.

Liao, C., Yanyongjie, Wu, C., Huang, H. (2004). "Study on the distribution and quantity of biomass residues resource in China." Biomass and Bioenergy **27**(2): 111-117.

Life Cycle Associates (2007). BEACCON model (http://www.lifecycleassociates.com/).

Loulos, J., Alternative Solid Fuels Manager, personal communication with A. Murray (April 11, 2008). Use of alternative solid fuel in cement kilns. Sugar Creek, MO.

Mani, S., L. G. Tabil, et al. (2004). "Grinding performance and physical properties of wheat and barley straws, corn stover and switchgrass." Biomass and Bioenergy **27**(4): 339-352.

Mansaray, K., Ghaly, A. (1997). "Physical and Thermochemical Properties of Rice Husk." Energy Sources, Part A: Recovery, Utilization, and Environmental Effects **19**(9): 989-1004.

Maxham, J. (1992). Conversion of paper mill sludge into papermaking pulp and filler products, Division of Pollution Prevention and Environmental Assistance, North Carolina Department of Environment and Natural Resoures**:** 14.

McGray, S., Process Engineer, personal communication with A. Murray. (February 18, 2008). Use of tires as alternative fuel in cement manufacturing, California Portland Cement Company, Colton, CA.

McIlveen-Wright, D. R., Huang, Y., Rezvani, S., Wang, Y. (2007). "A technical and environmental analysis of co-combustion of coal and biomass in fluidised bed technologies." Fuel **86**(14): 2032-2042.

Metz, B., Davidson, O., Bosch, P., Dave, R., Meyers, L. (eds) (2007). Climate Change 2007: Mitigation of Climate Change. Contribution of Working Group III to the Fourth Assessment Report of the IPCC. New York, NY, Intergovernmental Panel on Climate Change.

Mirabile, D., M. I. Pistelli, et al. (2002). "Thermal valorisation of automobile shredder residue: injection in blast furnace." Waste Management **22**(8): 841-851.

Mokrzycki, E. and A. Uliasz- Bochenczyk (2003). "Alternative fuels for the cement industry." Applied Energy **74**(1-2): 95-100.

Mokrzycki, E., A. Uliasz-Bochenczyk, et al. (2003). "Use of alternative fuels in the Polish cement industry." Applied Energy **74**(1-2): 101-111.

Murray, A., Horvath, A., Nelson, K. (2008). "Hybrid life-cycle environmental and sludge cost inventory of sewage sludge treatment and end-use scenarios: A case study from China." Environ Sci Technol **DOI: 10.1021/es702256w**.

National Bureau of Statistics of P.R. China (2007). China Statistical Yearbook, China Statistics Press.

National Bureau of Statistics of P.R. China. (2008). "Primary Statistics for Rural China."   Retrieved May 2008, from http://www.stats.gov.cn/tjgb/nypcgb/qgnypcgb/t20080226_402464495.htm.

Peltier, R. (2003). "Mercury removal standards are coming. Where's the technology? (Cover story)." Power **147**(4): 40.

Portland Cement Association (2006). Report on Sustainable Manufacturing.

Price, L., Galitsky, C. (2007). Opportunities for improving energy efficiency and increasing economic output in Chinese cement kilns. ACEEE Summer Study on Energy Efficiency in Industry.

Prisciandaro, M., G. Mazziotti, et al. (2003). "Effect of burning supplementary waste fuels on the pollutant emissions by cement plants: a statistical analysis of process data." Resources, Conservation and Recycling **39**(2): 161-184.

Realff, M., Lemieux, P., Lucero, S., Mulholland, J., Smith P (2005). Characterization of transient puff emissions from the burning of carpet waste charges in a rotary kiln combustor. Cement Industry Technical Conference, 2005. Conference Record.

Reijnders, L. (2007). "The cement industry as a scavenger in industrial ecology and the management of hazardous substances." Journal of Industrial Ecology **11**(3): 15-25.

Resource Management Branch (1996). Composting Factsheet. Abbotsford, BC, Canada, British Columbia Ministry of Agriculture Food and Fisheries.

RMA (2006). Scrap Tire Markets in the United States 2005 Edition, Rubber Manufacturers Association**:** 93.

Ryu, C., A. N. Phan, et al. (2007). "Combustion of textile residues in a packed bed." Experimental Thermal and Fluid Science **31**(8): 887-895.

Saft, R. (2007). "Life cycle assessment of a pyrolysis/gasification plant for hazardous paint waste." <u>The International Journal of Life Cycle Assessment</u> **12**(4): 230-238.

Schmidthals, H. and H. Schmidthals (2003). <u>The pre-combustion chamber for secondary fuels development status of a new technology</u>. Cement Industry Technical Conference, 2003. Conference Record. IEEE-IAS/PCA 2003.

Seyler, C., Hellweg, S., Monteil, M., Hungerbühler, K. (2005). "Life cycle inventory for use of waste solvent as fuel substitute in the cement industry-a multi-input allocation model " <u>The International Journal of Life Cycle Assessment</u> **10**(2): 120-130.

Seyler, C., T. B. Hofstetter, et al. (2005). "Life cycle inventory for thermal treatment of waste solvent from chemical industry: a multi-input allocation model." <u>Journal of Cleaner Production</u> **13**(13-14): 1211-1224.

Shih, P., Chang, J., Lu, H., Chiang, L. (2005). "Reuse of heavy metal-containing sludges in cement production." <u>Cement and Concrete Research</u> **35**(11): 2110-2115.

Siddique, R., J. Khatib, et al. "Use of recycled plastic in concrete: A review." <u>Waste Management</u> **In Press, Corrected Proof**.

Subramanian, P. M. (2000). "Plastics recycling and waste management in the US." <u>Resources, Conservation and Recycling</u> **28**(3-4): 253-263.

US Environmental Protection Agency. (2008). "Standards for Hazardous Air Pollutants for Hazardous Waste Combustors." from http://www.epa.gov/epaoswer/hazwaste/combust/finalmact/index.htm#finaloct.

UNEP Chemicals (2005). Standardized Toolkit for Identification and Quantification of Dioxin and Furan Releases. Geneva, Switzerland, United Nations Environment Programme Chemicals**:** 194.

UNEP Chemicals (2005). Toolkit for Identification and Quantification of Mercury Releases. Geneva, Switzerland, United Nations Environment Programme Chemicals**:** 282.

US EPA. (2007). "Automotive Parts."   Retrieved February 22, 2008, from http://www.epa.gov/garbage/auto.htm.

Vaajasaari, K., M. Kulovaara, et al. (2004). "Hazardous properties of paint residues from the furniture industry." <u>Journal of Hazardous Materials</u> **106**(2-3): 71-79.

Vaccaro, M. and M. Vaccaro (2006). <u>Burning alternative fuels in rotary cement kilns</u>
<u>Burning alternative fuels in rotary cement kilns</u>. Cement Industry Technical Conference, 2006. Conference Record. IEEE.

Vallet, F., Resource Recovery Manager, personal communication: Murray, A. (January 26, 2007). Lafarge China cement manufacturing overview. Lafarge Shui On Cement, Chongqing, Sichuan Province, China.

van Oss, H., Padovani, A. (2002). "Cement manufacture and the environment part I: chemistry and technology." <u>Journal of Industrial Ecology</u> **6**(1): 89-105.

Wang, X. (2007). Improving Energy Efficiency, International Cement Review.

WBCSD (2002). Toward a Sustainable Cement Industry: Environment, Health, and Safety Performance Improvement, World Business Council for Sustainable Development**:** 58.

WBCSD (2004). Formation and Release of POPs in the Cement Industry, World Business Council for Sustainable Development for Foundation for Industrial and Scientific Research of Norway.

WBCSD (2006). Formation and Relsease of POPs in the Cement Industry. Cement Sustainability Initiative, World Business Council for Sustainable Development**:** 200.

Ye, T. H., J. Azevedo, et al. (2004). "Co-combustion of pulverized coal, pine shells, and textile wastes in a propane-fired furnace: Measurements and predictions." Combustion Science and Technology **176**(12): 2071-2104.

Zementwerke, V. (2002). Environmental Data of the German Cement Insustry 2001, German Cement Works Association**:** 52.

Zhou, J., Zhang, H., Wang, J.W., Gan, Y.P., Wang, H.C. (2006). Biosolids management and legislation in China. Beijing, Beijing Drainage Group CO., Ltd.**:** 11.