Emissions Impacts of Alternative Fuels Combustion in the Cement Industry

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Executive Summary

With over 7% of global CO_2 emissions, decarbonization of the cement industry will play a key role in achieving the Paris Climate Agreement targets. The deep decarbonization of the cement industry can be achieved through measures such as demand reduction and material efficiency, clinker substitution, alternative binding materials, carbon capture and storage, energy efficiency improvements, electrification, and the use of alternative fuels. The present report analyzes the effect of replacement of fossil fuels with alternative fuels on the CO_2 and non-CO_2 air pollutant emissions in the U.S. cement industry.

Some of the most commonly used alternative fuels in the cement industry are biomass, industrial and domestic waste materials, scrap tires, and sewage sludge. The high temperatures, long residence times, and alkaline environment in the cement kiln can prevent the formation of hazardous volatile compounds, making it a suitable option for co-processing waste materials as alternative fuels during cement production. Although the substitution of fossil fuels such as coal and pet coke with alternative fuels can potentially reduce total CO_2 emissions from the cement industry, the reduction potentials are often marginal (in the range of 1% - 5% for most cases and up to 18% of current CO_2 emissions in a few cases) and depend on the source of biogenic emissions. Moreover, due to higher concentrations of sulfur, nitrogen, chlorine, heavy metals, or other volatile matter in some alternative fuels, co-processing can increase emissions of non-CO_2 air pollutants of concern in some cases.

In this study, we provide a summary of the required properties, pre-processing methods, typical substitution rates, fuel dosing systems, technical challenges for substituting conventional fossil fuels with alternative fuels, and their impact on CO_2 and non-CO_2 emissions in the U.S. cement industry. The study focuses on the following alternative fuels: scrap tires, waste plastic, municipal solid waste, waste oil, biomass, and sewage sludge.

About 73% of U.S. cement plants are using some share of alternative fuels in their fuel mix. The potential impact of the co-processing of alternative fuels in the U.S. cement industry on the emissions of CO_2 and non-CO_2 air pollutants is analyzed for three scenarios: 1) 20% Replacement Scenario: In this scenario, 20% of coal and pet coke is replaced with alternative fuels and natural gas in the total fuel mix of the U.S. cement industry, and 2) 50% Replacement Scenario: In this scenario, 50% of coal and pet coke is replaced with alternative fuels and natural gas in the total fuel mix. 3) 100% Replacement Scenario: In this scenario, the entire share of coal and pet coke is replaced with alternative fuels and natural gas in the total fuel mix (see Appendix 3 for scenario description).

Based on our analysis, the impact of co-processing of alternative fuels on CO_2 stack emissions from the U.S. cement industry was marginal for most of the alternative fuels studied, especially if biogenic CO_2 emissions are not considered carbon-neutral (Figure ES1). The co-processing of waste oil represents the maximum potential for reducing CO_2 emissions from the U.S. cement industry (1% -7% CO_2 abatement for the scenarios studied). Co-processing of sewage sludge and scrap tires represents the CO_2 abatement potentials in the range of 1% to 5% across three scenarios studied, whereas municipal solid waste and biomass represent the lowest CO_2 abatement potential (<2% CO_2 abatement across all three scenarios). Replacing coal and pet coke with natural gas in the cement kiln represents higher potential than alternative fuels co-processing for CO_2 emissions reduction from the U.S. cement industry (2% - 12% across all the scenarios studied).
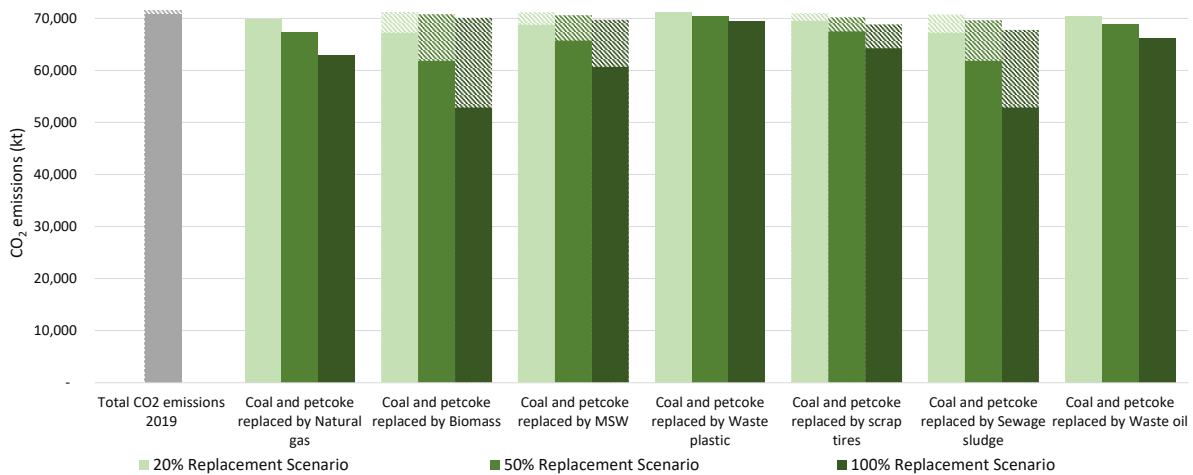
Figure ES1. Annual total CO_2 emissions (energy-related + process-related) after replacing 20%, 50% and 100% of coal and pet coke with various alternative fuels and natural gas in the U.S. cement industry in 2019 (Source: this study).

Note: the shaded part of the bars indicates the share of CO_2 emissions that are biogenic.

Based on the impact analysis of non-CO_2 air pollutant emissions, SO_2 emissions from the U.S. cement industry marginally increase when coal and pet coke are replaced with scrap tires (1%-4% across all three scenarios) or municipal solid waste (0.5%-1% across all three scenarios). Conversely, SO_2 emissions are lower when coal and pet coke are replaced with biomass or waste oil (4%- 48% across all scenarios studied). Co-processing of plastic waste represents the most considerable potential for SO_2 emissions reduction (16% -82% across all three scenarios).

Co-processing of waste oil represents the largest NOx reduction potential (17% -87% for all the scenarios studied). Sewage sludge, municipal solid waste, and scrap tires co-processing represent the potential in the range of 14% to 80% across all scenarios studied. The co-processing of biomass represents the lowest potential (5% to 27% across all three scenarios) for NOx emissions reduction from the U.S. cement industry.

Co-processing of all alternative fuels studied in this report can result in a reduction in particulate matter (PM) emissions, ranging from 8% to 75% across all scenarios studied. Similar to CO_2 emissions, replacing coal and pet coke with natural gas can potentially have more significant impact on the reduction of non-CO_2 emissions from the U.S. cement industry.

According to the U.S. Environmental Protection Agency (EPA) exposure to air pollutants such as SO_2, NOx and PM can cause a variety of respiratory health effects, including inflammation of the lining of the lungs, reduced lung function, and respiratory symptoms, increased susceptibility to respiratory infection, premature mortality, aggravation of cardiovascular disease, decreased lung function growth, exacerbation of allergic symptoms, neurodevelopmental effects such as lowered IQ and behavioral problems, reduction in the capacity of the blood to carry oxygen, thereby decreasing the supply of oxygen to tissues and organs such as the heart, and many other negative health effects. Emissions of these air pollutants disproportionately affect the communities in the vicinity of the cement plants, which are often low-income, disadvantaged communities. Hence, the air pollutants originating from cement manufacturing facilities in the U.S. are regulated under the programs such as National Emissions Standards for Hazardous Air Pollutants (NESHAP), Clean Air Act (CAA) and National Air Ambient Air Quality Standards (NAAQS).

To comply with the regulations, emissions of air pollutants can be controlled by various primary and secondary techniques, either by limiting the formation of pollutants in the first place or by capturing the pollutants from the exhaust gas or by a combination of both. NOx emissions can be controlled through techniques such as flame cooling, using low NOx burners, mid-kiln firing, mineralized clinker, staged combustion, and catalytic reduction with reduction efficiencies up to 95%. The emissions of SO_2 can be controlled by absorbent addition, wet or dry scrubbers, and activated carbon. These techniques have reduction efficiencies up to 95%. Dioxin and furan emissions can be controlled by minimizing their formation through techniques such as kiln optimization and careful selection of fuels and their dosing points. Electrostatic precipitators and fabric filters are the most widely commercially available technologies to control the emissions of PM.

It is important to note that the analysis presented in this report only looks at expected stack emissions in the U.S. cement industry from substituting coal and pet coke with various alternative fuels and natural gas. The scope of the analysis is limited: it does not consider the potential implications of such substitutions upstream (e.g., methane leaks, waste pre-processing energy penalty, etc.); it does not consider emissions profile of the counterfactual fate of waste such as the CO_2 and non-CO_2 emissions that could result if the waste were otherwise incinerated or landfilled; and, it does not consider whether and how the use of natural gas could impact other natural gas end-users. Moreover, the report does not explore whether such substitutions could lead to "lock-in" of alternative fuels or natural gas nor does it provide an exhaustive assessment of air pollutant emissions that could be reasonably expected depending on the type of fuel used (e.g., VOCs or PFAS).

While there is brief discussion of how substituting conventional fossil fuels with alternative fuels could potentially have other benefits, such as recovery of the energy content of waste, lowering cement production costs in some cases, and reducing waste sent to landfills, it is not a major focus of this report. The main finding of the analysis is that the co-processing of alternative fuels, especially waste-derived fuels, will not result in a meaningful reduction in the CO_2 emissions of a cement plant, especially if biogenic CO_2 emissions are not considered carbon-neutral, and can potentially be associated with negative environmental and health impacts to the local environment and communities.

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1 Introduction

Cement manufacturing is one of the most energy-and carbon-intensive industries. The cement industry is responsible for around 7% of total global CO_2 emissions (Hasanbeigi et al., 2021). In 2020, overall global cement production was about 4,300 Mt, while the United States ranked fourth globally with 89 Mt of cement production (USGS, 2022). Global production of cement has been increasing at a steady rate for the past couple of decades and it is expected to continue increasing in the future (IEA, 2018). Thus, the decarbonization of the cement industry will play a key role in achieving the Paris Climate Agreement targets.

Cement manufacturing typically consists of three main steps: (1) Raw materials and solid fuels are pre-processed using techniques like grinding, crushing, and drying. (2) Clinker production via either wet or dry process in a kiln where raw materials are heated up to the temperatures of 1500°C leading to the decomposition of calcium carbonate into calcium oxide and CO_2. (3) Clinker is then ground with gypsum and other additives in a mill to produce cement.

As a result of CO_2 emissions from calcium carbonate decomposition, the majority of CO_2 emissions from cement manufacturing are associated with the chemical reaction in the process and not the energy use. However, fuel-related emissions still contribute to approx. 42% of total CO_2 emissions from the U.S. cement production (DOE, 2022). The CO_2 emissions from the cement industry can be reduced through material efficiency in the construction sector, energy efficiency improvements, clinker substitution, alternative binding materials, switching from traditional fuels to alternative low/no-carbon fuels, and carbon capture, utilization, and storage (IEA, 2018). According to a recent report by GCCA, switching from fossil fuels to alternative fuels is expected to have less than 10% contribution to decarbonization of the cement and concrete industry globally by 2050 (GCCA, 2021).

Waste materials such as fractions of municipal waste, hazardous and non-hazardous industrial wastes, agricultural wastes, etc. have been successfully pre-processed into waste-derived alternative fuels and co-processed with conventional fossil fuels in cement kilns across the world (GIZ/Holcim, 2020). Co-processing of waste in the existing cement kiln is less expensive compared to investing in new waste-to-energy alternatives such as waste material incinerators (Zhu, 2011; ECRA, 2016). Moreover, high temperatures, long residence times and alkaline environment in the cement kiln contribute to the prevention and destruction of hazardous organic compounds while binding volatile compounds in the clinker chemistry (GIZ/Holcim, 2020). Hence, co-processing alternative fuels with conventional fossil fuels is commonly advocated as one of the pathways for overall CO_2 emissions reduction and also a waste management strategy.

It should, however, be noted that the co-processing of alternative fuels in the cement kiln should not be a primary waste management strategy. US EPA's waste management hierarchy recommends source reduction, reuse, recovery, recycling and composting as preferred strategies from a sustainability and climate perspective compared to energy recovery. Despite the widespread practice of alternative fuels co-processing in the cement industry, poor selection of alternative fuels, improper pre-processing and co-processing, or improper substitution rates in the fuel mix can result in negative environmental and health consequences in the form of higher CO_2 or non-CO_2 air pollutant emissions (US EPA 2022d).

This report begins with the current status of alternative fuels used in the U.S. cement industry, followed by a summary of analysis of the most widely used alternative fuels, including their typical co-processing rates, dosage systems, and technical challenges. The focus of the report is to present the impact of the co-processing of alternative fuels in the cement kiln on CO_2 and non-CO_2 emissions from the U.S. cement industry. The emissions of CO_2 constitute more than 99% of total GHG emissions from the cement industry (Hasanbeigi et al., 2019). As a result, the analysis focuses primarily on CO_2 emissions.

In addition to CO_2 emissions, the cement industry is also responsible for a considerable amount of non-CO_2 air pollutant emissions (Hasanbeigi et al., 2022). The impact of alternative fuel co-processing on the emissions of other air pollutants such as SO_2, NOx, Particulate matter, and dioxins and furans is also presented in the report. The analysis focuses on scope 1 and scope 2 emissions from the cement industry (refer to appendix 1 for definitions). Due to the lack of data availability, scope 3 emissions are not considered in the analysis. Total CO_2 and non-CO_2 emissions from the U.S. cement industry are estimated based on the emission factors reported by the US Environmental Protection Agency (EPA), European Environmental Agency (EEA), and other literature sources (refer to the appendix for details on boundaries and methodology used in this study).

2 Current Status of Alternative Fuel Use in the U.S. Cement Industry

U.S. cement manufacturers used alternative fuels to fulfill about 16% of fuel-related energy demand in 2019 (USGS, 2022). According to the United States Geological Survey (USGS, 2022), about 73% of U.S. cement plants are using some share of alternative fuels in their fuel mix, with waste tires contributing 21%, solid waste contributing about 22% and other liquid wastes (including hazardous materials) contributing to around 57% of the total energy provided by alternative fuels (USGS, 2018). The other materials include engineered fuels, refuse derived fuels, agri-waste, ashes, biofuels, biomass, carpet, charcoal, cherry pits, coal pond fines, coke breeze, filter fluff, flex coke, glycerin, landfill gas, nylon fluff, pecan shells, plastics, rice hulls, sawdust, shingles, spent activated carbon, spent pot liner, textile waste, wood, and even other more unique materials (PCA, 2019).

The composition of fuel consumption in the U.S. cement industry has changed consider-ably from 1996 to 2019. The share of thermal energy demand covered by coal and coke has dropped from 74% to about 59%, while natural gas has increased from just over 7% to nearly 25% in the past two decades. Alternative fuel use in 1996 represented just 2% of the energy consumption in cement plants, but by 2019, that figure jumped to 16% of total fuel demand (Figure 1) (PCA 2019; USGS, 2022).

Of the 16% of fuel demand covered by alternative fuels in the U.S. cement industry, about 57% comes from liquid wastes (waste oils & solvents). The share of energy provided by scrap tires has remained at 21% of alternative fuels. The share of 'municipal solid wastes (MSW)' rose from just below 5% in 1996 to more than 21% in 2019 (PCA, 2019).
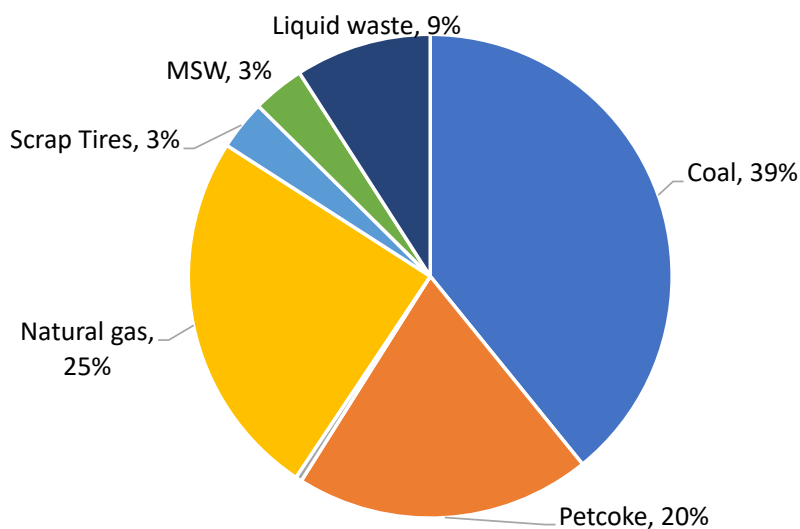
Figure 1. Fuel mix of the U.S. cement industry in 2019 (USGS, 2020; EPA, 2022)

Based on the fuel consumption reported by USGS, the emission factors reported by the U.S. EPA and the energy intensity of the U.S. cement industry, process-related emissions (i.e., emissions from calcium carbonate decomposition) constitute about 57% of total CO_2 emissions and the other 43% of emissions can be attributed to energy-related CO_2 emissions (Figure 2).

As a result of their overall high share in the total fuel consumption and the relatively higher CO_2 emission factors, the consumption of coal and petroleum coke are responsible for about a quarter of total CO_2 emissions from the U.S. cement industry. The consumption of natural gas represents only 6% of total CO_2 emissions. The alternative fuels together represent only about 5% of total CO_2 emissions from the U.S. cement industry, whereas indirect emissions from electricity consumption contribute up to 7%.
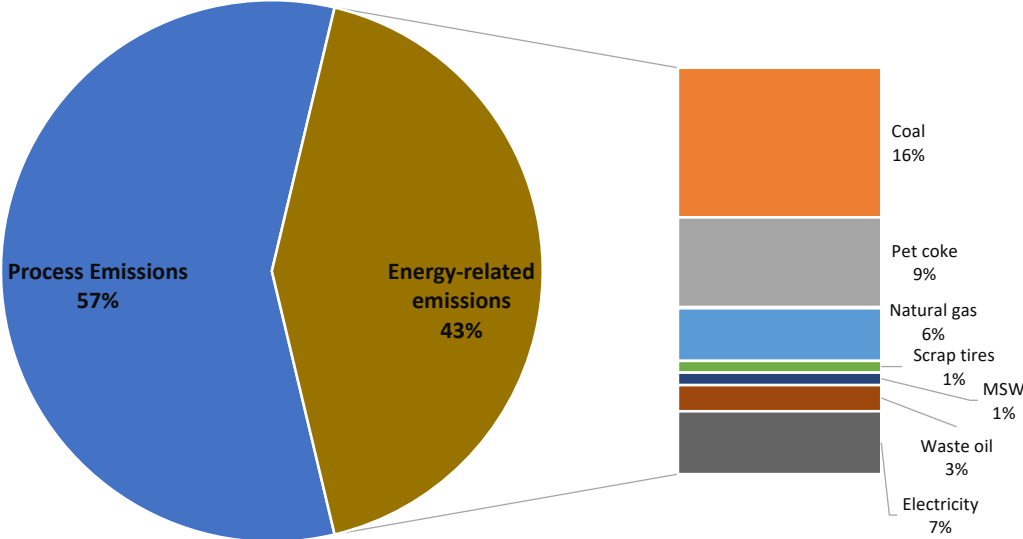
Figure 2. Shares of CO_2 emissions from the U.S. cement industry in 2019 (USGS, 2022; EPA, 2022)

CO_2 emissions from the cement industry in California

With its 11% share of total U.S. cement production, California is the second largest cement-producing state in the U.S. after Texas (USGS, 2022). California's nine cement plants produced about 12.4 Mt of cement in 2019[1] and consumed about 34.3 petajoules (PJ) of fuel (USGS, 2022; CARB, 2021). California's cement industry was responsible for about 2.8 Mt CO_2 emissions in 2019. The vast majority of the fuel-related CO_2 emissions come from coal consumption (68%) and petroleum coke (17%). Natural gas is responsible for 9% of total fuel-related CO_2 emissions from California's cement industry, whereas alternative fuels such as scrap tires and municipal solid wastes (MSW) contributed to only about 5% of fuel-related CO_2 emissions from the cement industry in California in 2019. Compared to the U.S. average, California's cement plants consume more coal and coke and fewer alternative fuels compared to the overall U.S. cement industry. Given the availability of relatively low-cost natural gas in the U.S., California has a substantial potential to move away from coal and coke to natural gas in the near term as a transition fuel and substantially reduce its energy-related CO_2 emissions in the cement industry.

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1   Although the CO_2 emissions in this section are presented for nine cement plants, as of December 2022, there are seven cement producing facilities in California (USGS, 2022).
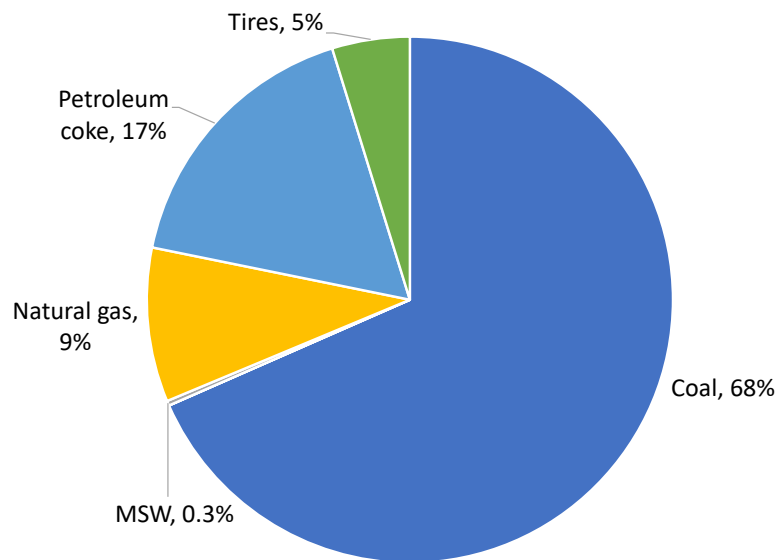
Figure 3. Fuel-related CO$_2$ emissions from California's cement industry in 2019 (CARB, 2021)

3 Quality Criteria for Selection of Alternative fuels

When done in accordance with environmental standards and regulations, replacing fossil fuels like coal or petroleum coke with alternative fuels in cement production can potentially lead to a reduction in CO_2 emissions. However, it should be noted that the CO_2 emissions reduction in most cases are marginal, especially if biogenic CO_2 emissions are not considered carbon-neutral. Also, in some cases, poor selection of alternative fuel or their substitution rate can result in an increase in CO_2 or other non-CO_2 air pollutant emissions. Moreover, the organic and inorganic contents of alternative fuels are captured in clinker and may have an influence on the quality of clinker produced. In order to avoid the adverse effects of alternative fuel combustion in cement plants, certain quality criteria are implemented while selecting a suitable alternative fuel. Table 1 below presents typical ranges of accepted concentrations of various components in the alternative fuels used by cement plants.

Table 1. Recommended composition of alternative fuels in the cement industry (European Commission, 2013)

Component	Accepted values
Moisture	<4%
Chlorine	0.1% - 1%
Sulfur	0.2% - 2%
Nitrogen	<1.4%
Polychlorinated biphenyls (PCB)	<50 ppm
Heavy metals	<2500 ppm
Mercury (Hg)	<10 ppm
Cadmium (Cd) + Titanium (Ti)	<1000ppm
Ash content	<0.5%
Calorific values	>17 GJ/t-fuel

Figure 4 below presents the composition of the most widely used alternative fuels in cement industry, along with coal. Waste plastic and waste tires have higher carbon content by weight than coal. However, some fraction of the carbon content of the tires is considered biogenic. MSW, sewage sludge, and biomass have higher ash contents by weight than coal. Sewage sludge typically has higher nitrogen content by weight compared to coal, and scrap tires have marginally higher sulfur content than that of coal on a weight basis. MSW and waste plastics are observed to have marginally higher chlorine content than coal.
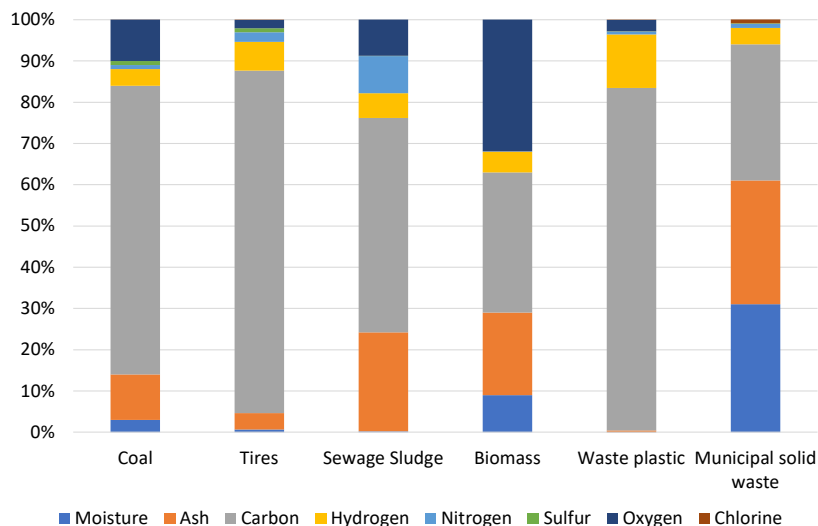
Figure 4. Composition of alternative fuels (% weight; adopted from Rahman et al. 2015)

3.1. Net Calorific Value

Alternative fuels in the cement industry are typically burned during the clinker production stage in the rotary kiln. Rotary kilns are designed for low volatile, high calorific value fuels such as petroleum coke, coal, and anthracite. As a result, the alternative fuels used to substitute fossil fuels for the main firing should have their calorific values above 18 to 22 GJ/t fuel. However, high-volatile fuels with lower calorific values can be used in the pre-calciner section of the kiln. The calorific value of the alternative fuels used in the pre-calciner can be between 11 to 13 GJ/t of fuel (ECRA, 2016). Figure 5 presents the average net calorific values of the most commonly used conventional and alternative fuels (before pre-treatment) in the cement industry.[2]
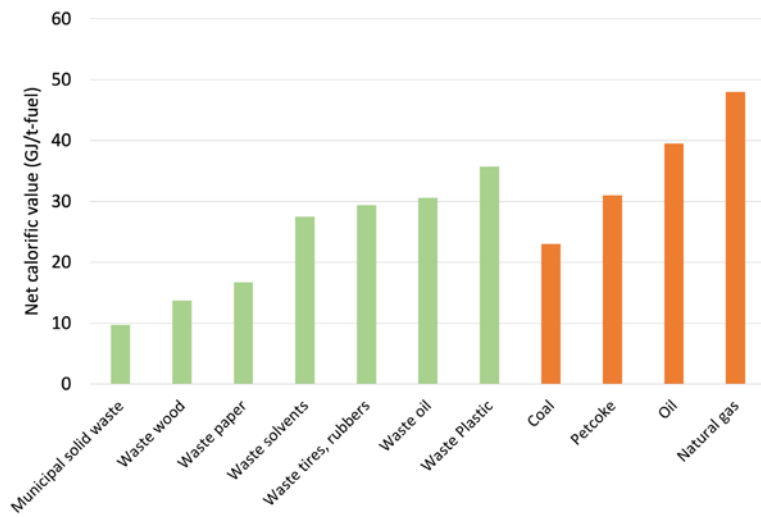
Figure 5. Net calorific values of conventional and alternative fuels (before pre-treatment) (ECRA, 2016; EPA, 2020b)

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2   Calorific values are typically higher after pre-treatment.

3.2. Moisture Content

The moisture content of the alternative fuels affects their heating values. Lower moisture contents are advised for better efficiency of fuel consumption. Typical moisture contents of alternative fuels are shown in Table 2. Alternative fuels with higher moisture content are subjected to mechanical or thermal pre-processing in order to reduce the moisture content.

Table 2. Moisture content of most common alternative fuels (Rahman et al., 2015)

Alternative Fuel	Moisture content (%)
Used tires	0.6
Spent pot liner	0.6
MSW	31.2
Dried Sewage Sludge	Variable
Biomass	6-12
Plastic waste	Variable
Waste oils and solvents	<3

3.3. Ash Content

The ash produced as a result of burning the fuels is incorporated in the clinker. Thus, it is necessary to monitor the composition and content of ash to make sure it meets the requirements for clinker production. Table 3 provides the percentage ash content in various alternative fuels. Similar to moisture content, the ash content of the alternative fuels is also controlled with mechanical or thermal pre-processing.

Table 3 . Typical ash contents of various alternative fuels (Rahman et al., 2015)

Alternative Fuel	Ash content (%)
Used tires	4.8
MSW	30.0
Plastic waste	0.3
Waste oil	2.4
Biomass	20.0
Sewage sludge	24.0

3.4. Chlorine Content

The presence of chlorine affects the kiln's performance directly and indirectly. Trace levels of chlorine in the feed of fuel lead to the formation of acidic gases such as hydrogen chloride (HCl). The build-up of chlorine on the kiln surface can lead to corrosion. Chlorine can trigger the volatility of heavy metals and can cause emissions of dioxins and furans (Ma, 2010). If the chlorine content reaches 0.3 to 0.5%, it is controlled by operating a bypass to extract a part of flue gas, which results in 0.02 GJ/t-clinker of additional energy demand[3] (Murray and Price, 2008). The typical chlorine content in alternative fuels varies in the range of 0.14% to 1% (see Figure 4).

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3   Average energy consumed per ton of clinker produced in the U.S. is about 3 GJ/t.

3.5. Heavy Metals Content

The majority of heavy metals introduced in the kiln are incorporated in clinker or contained by the emission control system (EPA, 2020a). For example, the lead content of the alternative fuels despite being at least twice as high to that of coal (Table 4), is typically incorporated into minerals of clinker either as silicate or sulfate (Huang et al., 2021). As a result, switching from coal to alternative fuels does not substantially change the levels of heavy metal emissions from the cement plant. However, emissions of Mercury (Hg) and Cadmium (Cd), being volatile, are especially hard to control through existing emission control technologies and as a result, the only way to control their emissions is by limiting their concentration in raw materials or fuels (Murray and Price, 2008). The typically suggested limits for the concentration of heavy metals in fuels (based on data gathered from EU cement plants) are presented in table 1 and typical concentrations of heavy metals in alternative fuels are presented in Table 4.

Table 4. Typical values of heavy metals in coal and alternative fuels (ppm of dry substance; European Commission, 2013).

	Coal	Sewage sludge	Waste oil	Waste solvent	Waste plastic	Tires
Mercury (Hg)	1.3	1.2	0.47	0.6	0.6	0.02
Cadmium (Cd)	0.51	1.02	0.5	0.6	15	3.9
Chromium (Cr)	68.9	28	8	30	150	26
Lead (Pb)	10.9	25.5	59	180	150	28

4   Pre-Treatments of the Alternative Fuels

For co-processing of alternative fuels in the cement industry, their properties should remain in a certain range. Solid wastes (e.g., MSW) vary in size, semi solid wastes (e.g., sludge) have lower calorific value due to high moisture content, liquid wastes (e.g., solvents, waste oils) can have different purities, viscosities, and other properties. On-site or off-site pre-processing facilities can be used for the treatment of alternative fuels in order to increase their suitability for co-processing in cement plants. Pre-treatment processes include mechanical, thermal, and biological treatments to reduce the particle size, improve homogeneity, reduce the moisture content or improve the calorific value (see Table 5). The following section briefly describes some of the most widely implemented pre-treatment methods for alternative fuels in the cement industry.

Table 5. Summary of pre-treatment processes for alternative fuels

Type of alternative fuel	Fuels	Pre-treatment
Solid waste	MSW	Sorting, milling, drying, aerobic degradation, anaerobic degradation
	Scrap tires, Waste plastic	Shredding, grinding
Semi-solid waste	Sewage sludge	Mixing and homogenization, Drying
Liquid wastes	Industrial solvents, waste oils	Filtration, centrifugation, emulsification, torrefaction and pyrolysis

Table 6 presents the additional energy consumption and corresponding additional CO_2 emissions from the pre-treatment of alternative fuels. The process of drying the sewage sludge is the most energy-intensive pre-treatment. Sewage drying can take place either at the municipal facility or at the cement plant. In most cement plants however, the heat needed for drying is provided by the excess heat available from the cement kiln flue gas which results in no additional CO_2 emissions if drying is carried out at the cement plant. If pre-treatments are carried out at the location of the cement producing facility, they can potentially result in additional CO_2 emissions from the cement manufacturing facility. These additional emissions can range between 1% for scrap tires shredding and 7% for grinding of dried sewage sludge compared to the current CO_2 emissions per tonne of clinker from the U.S. cement industry.

4.1. Milling and Drying

Alternative fuels like mechanically dewatered sludge, pulp waste, or MSW have high moisture content and relatively lower heating values. These fuels can be made more suitable by thermally drying them using excess heat from the kiln system. If the fuels are too coarse, they are fed to the mills to increase the fineness. Some mills are also equipped with thermal dryers, thus, simultaneously increasing the heating value and fineness of the alternative fuels and making them more suitable for the firing zone (ECRA, 2016). Hammermills are most commonly used for the size reduction of coarse waste materials. Hammermills can have either vertical or horizontal rotors. Horizontal rotors are typically used for the more heterogenous waste materials like MSW. Waste materials are fed through the opening of the mill, and they are crushed with the swinging hammers until they pass through the grates on the other side of the mill, thus providing a uniform particle size (Hasanbeigi, 2012).

Table 6 . Additional energy consumption and corresponding CO_2 emissions from the pre-treatment of alternative fuels and coal (Hasanbeigi et al., 2012; GIZ/Holcim, 2020)

Fuel	Pre-treatment	Equipment	Specific energy consumption pre-treatment (GJ/t-fuel)	Specific energy consumption pre-treatment (GJ/t-clinker)	Additional CO_2 emissions (kg CO_2 / t-clinker)
Scrap tires	Size reduction	Shredder	0.05	0.01	7 (Electricity)
Sewage sludge (Dried)	Grinding		0.14	0.04	61 (Electricity)
Sewage sludge[1]	Drying	Rotating disc dryer	10.00	3.09	164[1] (Fossil fuels)
MSW	Size reduction	Shredder	0.04	0.01	17 (Electricity)
MSW	Size reduction	Hammer mill	0.08	0.02	33 (Electricity
Waste plastic	Size reduction	Shredder	0.04	0.00	5 (Electricity)
Coal	Grinding	Ball drum	0.8	0.1	146 (Electricity)

[1] This number represents additional CO_2 emissions if sewage sludge is dried at the municipal facility. However, if the sludge drying takes place at the cement facility, the waste heat from kiln flue gases used to carry out drying and additional CO_2 emissions are considered to be zero.

4.2. Pre-Combustion and Gasification

Pre-combustion or gasification provides homogeneity, improves net calorific value, and reduces hazardous content, thus making waste materials more suitable to be used as alternative fuels. Typical pre-combustion chambers are equipped with a burner to support the calciner firing. During the pre-combustion, the fuel is ignited at a high temperature (1200°C), and with an additional retention time (up to 10 seconds). These conditions result in an enhanced burn-out of alternative fuels (ECRA,2016). There are some advanced systems commercially available that can increase the material retention time up to 45 min or use stepped combustion of more coarse waste materials. The mineral fraction and ashes of the waste and biomass materials are incorporated into the product and thereby recycled. The gasification process produces lean gas, which can be fed to the kiln inlet area where it is completely oxidized. Thus, homogenizing the energy input leads to the stabilization of the clinker burning process. The gasification can allow the use of low calorific value fuels (4 GJ/t to 6 GJ/t) as long as metal fractions are removed (ECRA,2016).

4.3. Hydrothermal Carbonization

Hydrothermal carbonization (HTC) is a process of carbonization of aqueous solution under high pressure and elevated temperatures. This process allows the use of any type of wet and waste biomass such as sewage sludge. The char resulting from the process has 70% to 90% carbon and has a calorific value similar to that of lignite (i.e., 12 to 24 GJ/t depending on the feedstock). The increase in the energy density of HTC char allows further substitution of fossil fuels by waste derived biomass fuel. However, the cost-effectiveness of HTC is currently a significant barrier for its wide adoption (ECRA, 2016).

4.4. Mechanical and Biological Treatment (MBT)

The mechanical treatments are typically used for preparing refused-derived fuel (RDF) from the non-biodegradable part of the waste, which includes industrial waste such as packaging and manufacturing waste, commercial dry waste and dry portion of MSW (e.g., metals, plastics, sizable pieces of cardboards, aluminum cans). Mechanical treatment is an established industry practice, and it typically involves coarse sorting, primary grinding, separation of ferrous fraction using a magnetic conveyor, sorting the rest of the ground fraction (manual or using trommel screen), and second fine grinding to achieve the desired particle size for RDF (IFC, 2017; Hasanbeigi, 2012).

Mechanical treatment is followed by biological treatment for the biodegradable fraction of the waste. The biological treatments are usually based on the anaerobic degradation process. The main purpose of this process is to reduce moisture content which is achieved by the heat generated during degradation process. MBTs can be employed independently, or they can also be used with landfills. The calorific values in the range 3 to 40 GJ/t have been reported for RDF produced using MBTs (Hasanbeigi et al., 2012). Figure 6 below presents a brief outline of MBT process and main technologies involved in it.
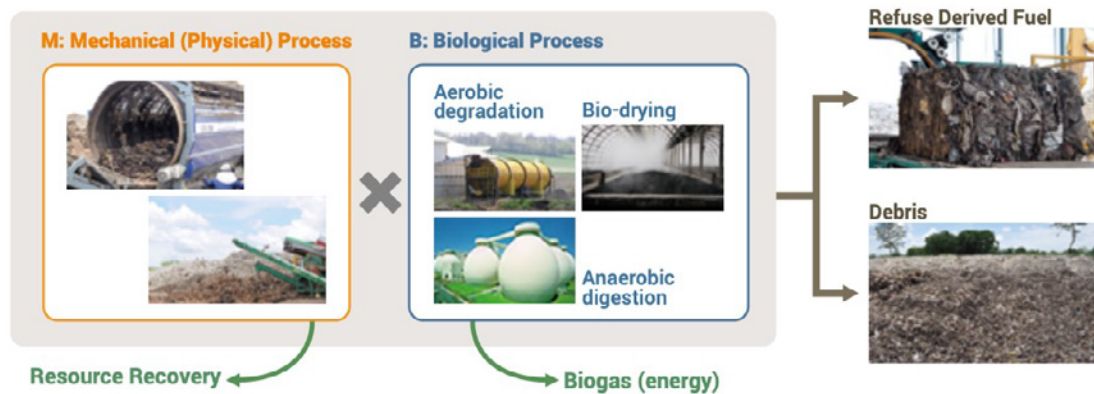

Figure 6. Brief outline of the mechanical and biological treatment to produce refused derived fuel (UNEP, 2020)

5   Technical Description of Various Alternative Fuels Used in the Cement Industry

Alternative fuels can be broadly classified as non-hazardous waste materials (agricultural biomass, MSW, sewage sludge, scrap tires, etc.) and hazardous waste materials (waste oil, spent solvents, paint residue, obsolete pesticides, etc.). The following section presents a qualitative assessment of selected alternative fuels. The assessment includes certain key criteria such as availability of alternative fuels, rate of substitution, environmental impact in terms of change in CO_2 and non-CO_2 emissions from the cement industry and technical challenges of adopting alternative fuels.

5.1. Scrap Tires

Scrap tires are one of the most widely used alternative fuels in the cement industry around the world, constituting 10% to 20% of the alternative fuels used in some of the largest cement producers in the world (Rahman et al., 2015). Tires can be used either whole or shredded. About 24% of recovered tires are currently being used in cement kilns in the U.S. (U.S. Tire manufacturer association, 2020). The high net calorific value of rubber makes tires the most comparable to fossil fuels in terms of energy efficiency for use in the cement industry (see Figure 5). The inert material constitutes about 27% of tires, which is entirely recovered and used in the clinker. The use of tires can also help reach the target iron content in case the natural raw material lacks the desired requirement. In general, burning tires results in the reduction of NOx emissions compared to burning coal or pet coke. However, in some cases, an increase in SO_2 emissions has been reported (Murray and Price, 2008).

Fuel dosage
For solid fuels, the feed point is determined by their degree of preparation, particle size and calorific value. Primary fuel dosage in the rotary kiln with preheater is done through the main burner, and the secondary dosage is done at the transition between the preheater and rotary kiln. The primary dosage is used for traditional fossil fuels, while the secondary dosage is used for alternative fuels such as tires. Tire dosing takes place in the flue gas chamber at 1000°C and material temperature at about 800°C (Nakomcic et al.,2017). The organic components in the tires then burn at the higher temperature calcination zone (i.e., 1100°C to 1200°C). Inorganic compounds are oxidized in the transition and sinter zones. The rate of tire feeding is very important since it influences the CO formation in the kiln. The feeding system for tires controls the feeding rate through a vacuum chamber with a gate.
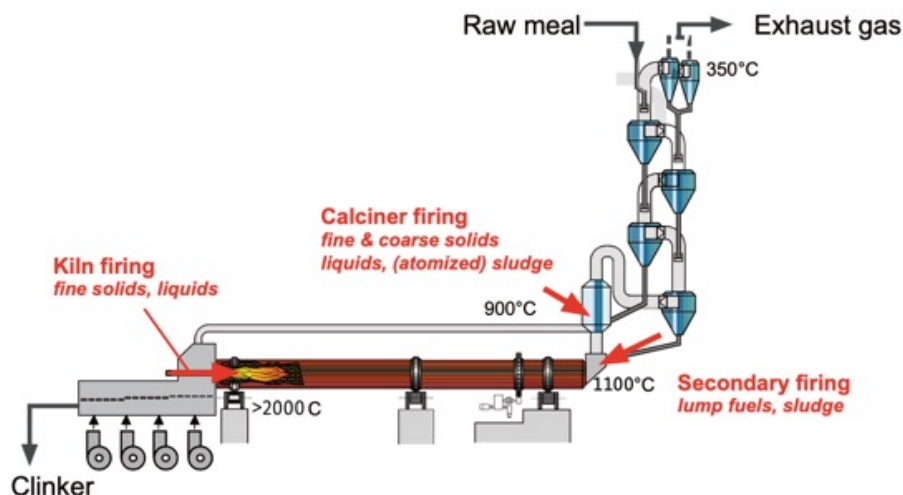

Figure 7. Feed points for alternative fuels co-processing (GIZ/Holcim, 2020)

Substitution Rate

The presence of zinc and sulfur dictates the limit for the use of tires for co-processing in the cement industry. Zinc present in the tires can affect the hydration and hardening of the cement. Overheating the kiln results in a reducing atmosphere that is conducive for volatile sulfur formation. As a result, the maximum substitution rates of scrap tires are reported to be below 20% of total fuel demand for a cement plant (Rahman et al., 2015; Nakomcic et al.,2017).

Technical challenges
If the whole tires have to be injected into the feed chute at the transition chamber of the rotary kiln, it reduces the possibility of achieving complete combustion of tires, reduces the thermal efficiency, and generates more flue gases (Pedersen, 2018). On the other hand, shredding tires require an additional investment and energy demand for the shredding equipment (Murray and Price, 2008).

5.2. Municipal Solid Waste (MSW)

Municipal solid waste (MSW) consists of everyday household items that are thrown away. It is also one of the most widely available alternative fuels. However, due to its very heterogeneous nature and varying properties, raw MSW requires pre-processing. The pre-pro-cessing can be done on-site by the cement manufacturing facility or offsite by the municipality. In general, SO_2 and NOx emissions can increase or decrease depending on the composition of municipal waste. However, the substitution of fossil fuels with MSW always results in some level of CO_2 and CO emissions reduction (Rahman et al., 2015).

Fuel dosage
After the pre-treatment, the MSW is made more suitable for the use in clinker production, referred to as Refused Derived Fuel (RDF) and is fed directly into the burning zone of the rotary kiln. Fuels are introduced in the kiln in a predefined ratio depending on the composition of waste. RDFs are typically injected using the injection apparatus that rotates with the kiln. As soon as the injector reaches a vertical position, the fuel drops to the center of the kiln (Hasanbeigi et al., 2012). A pneumatic conveying system is recommended for the transport of RDF in order to avoid damage to rotating parts of the conveyor system (European Commission, 2013). Due to the moisture content and odor, the RDF is typically stored in industrial hangers.

Substitution rate
Appropriate substitution rates for MSW vary greatly based on the composition and the level of pre-processing. Substitution rates from 2% for the MSW that undergoes only minimal mechanical processing to 30% of the total thermal demand for the MSW that has undergone Mechanical and biological pre-treatment process have been reported in the literature (Murray and Price, 2008; Kara et al. 2010; European Commission, 2013).

Technical challenges
MSW has a very heterogenous composition, and its properties vary over a wide range. These properties depend on the sources, season of the year and lifestyle and behavior of the local residents. Raw MSW typically has a high moisture content, low calorific value, high ash content and a wide range of particle sizes, making it less suitable for direct use in cement production (Hasanbeigi et al., 2012). To overcome the barrier of varying heating value, moisture content and variable particle size MSW has to be pre-processed using techniques such as separation, sorting, screening, blending, drying and pelletizing.

5.3. Plastic Waste

Plastic waste is one of the most readily available materials; it is available both as an industrial waste and municipal waste. Moreover, it has one of the highest calorific values among the alternative fuels. However, its application is limited by the chlorine content. It is recommended that the chlorine content of plastic should not exceed by 0.7% (on weight basis) in order to maintain the clinker quality (Murray and Price, 2008). Burning of plastic can cause an increase in the emissions of HCL, dioxins and furans. However, the kiln atmosphere can prevent their formation to some extent (Zierie and Ismail, 2019).

Fuel dosage
Fuels with high concentrations of volatile matter need longer time for complete burning. Plastic waste is also typically shredded during the preprocessing. As a result, the plastic wastes can be inserted in the kiln at the main firing system. Plastic is transported to the kiln either by conveyor belt or by pneumatic tubes (Zierie and Ismail, 2019).

Substitution rate
High concentrations of chlorine result in a high recirculation load leading to preheater clogging and affecting clinker quality (Chatterjee and Sui, 2019). Due to the possibility of high chlorine content, the substitution rate for plastic waste is limited to 5% of the total fuel mix (Murray and Price, 2008; Rahman et al., 2015).

Technical challenges
Solid fossil fuels are typically grinded to particle size below 100 μm. Plastic waste comes in a variety of shapes and sizes, and hence, it is necessary to install shredding equipment to produce uniform size particles for the injection in the kiln. The shredding equipment needs additional capital investment and energy (IFC, 2017).

5.4. Sewage Sludge

Sewage sludge is typically available as effluent from wastewater treatment. Sewage sludge can be incinerated in the cement kiln and the ash can be incorporated into the clinker. Wet sewage sludge can be used in wet process slurries. However, the sludge needs to be dried to reduce the moisture content below 1% for its use in the dry processes. Substitution of fossil fuels in clinker production by sewage sludge can result in decrease in NOx emissions but an increase in the SO_2 emissions (Rahman et al., 2015, Murray and Price, 2008). However, the levels of mercury in the sewage sludge can be higher than other alternative fuels.

Fuel dosage
Fuel dosage points in the kiln for alternative fuels depend on the concentration of volatile compounds present in the alternative fuel as well as temperature, residence time and type of operation. The amount of volatile matter in sewage sludge can be up to 70% (Rahman et al., 2015). As a result, they can be introduced in the main burner, mid kiln, in the riser duct or at the pre-calciner (Hasanbeigi et al., 2012).

Substitution rate
The substitution rate for sewage sludge can be up to 30% of the total thermal demand (Murray and Price, 2008). Lower injection velocities (close to 30 m/s) cause more fuel to burn close to the burners thus releasing more energy in the clinker burning zone. With this technique, the substitution rate of municipal sludge can be increased above 30% (Pedersen, 2018).

Technical challenges

High moisture content of the sewage sludge results in higher energy consumption compared to other alternative fuels. The chlorine content in the sewage sludge can enhance the volatilization of heavy metals like mercury (Hg), cadmium (Cd), and lead (Pb) (Murray and Price, 2008). High phosphorus content can further impede the use of sewage sludge as alternative fuel (IFC, 2017). The sewage sludge can be abrasive depending on its solid contents. The self-heating of sewage sludge can also cause fires or explosions. Special attention needs to be paid to these properties of the sewage sludge while designing a storage and handling system for the sewage sludge.

5.5. Biomass

It is critical that any kind of biomass used as a fuel in cement plants be from sustainable sources. The type of biomass used is highly variable and depends on the crops that are locally grown. Moreover, the carbon emissions impacts of biomass fuels vary widely, with many sources producing emissions substantially higher than fossil fuels, even after accounting for "biogenic" factors in net carbon accounting. Assuming the "carbon neutrality" of biomass fuels has been rejected in many instances in the peer-reviewed literature.

The European Commission has set sustainability criteria for large-scale biomass for heat and power, which address the practices used for sourcing feedstocks, but do not directly address the biogenic and non-biogenic GHG emissions themselves (European Commission 2022):

- Agriculture waste and residues, requiring evidence of the protection of soil quality and soil carbon, and for agriculture biomass, requiring evidence that the raw material is not sourced from highly biodiverse forests.
- Forest biomass, requiring bioenergy generators to demonstrate that the country of origin has laws in place a) avoiding the risk of unsustainable harvesting and b) accounting for emissions from forest harvesting. If such evidence cannot be provided, bioenergy generators need to demonstrate sustainability compliance at the level of the biomass sourcing area.
- New biofuels plants need to deliver at least 65% fewer direct GHG emissions than the fossil fuel alternative. New biomass-based heat and power plants need to deliver at least 70% (80% in 2026) fewer GHG emissions than the fossil fuel alternative.
- bioelectricity, requiring that large scale plants (above 50 MW) apply highly efficient cogeneration technology, or apply Best Available Techniques (BAT) or achieve 36% efficiency (for plants above 100 MW-), or use carbon capture and storage technology.

The criteria are complementary to the safeguards set out by EU climate and environmen- tal legislation, in particular by the Regulation on Land Use, Land Use Change and Forestry 2018/841. The regulation makes sure that all sectors contribute to the EU's 2030 emission reduction target, including the land use sector. The Commission's proposal (2021) to revise the Renewable Energy Directive promotes a gradual shift away from conventional biofuels to advanced biofuels (mainly produced from non-recyclable waste and residues) and other alternative renewable fuels (e-fuels). The EU's Biodiversity Strategy for 2030 considers that this approach should continue for all forms of bioenergy, and the use of whole trees and food and feed crops for energy production – whether produced in the EU or imported – should be minimized (European Commission 2022).

Because of its high moisture content and low heating value, adjustment to the burners is necessary (Murray and Price, 2008, Rahman et al, 2015). Despite the wide variety, wood and other types of waste from agriculture are the most widely used as alternative fuels (Uśon et al., 2013). As a result, average emissions factors for wood and agricultural biomass are used in the present analysis.

Fuel dosage
Biomass has a low calorific value. The co-processing of such alternative fuels can reduce the peak flame temperature and can lead to the modification of clinker properties. The biomass such as rice husk is typically pre-processed into fine solids. Fine solid alternative fuels can be mixed and suspended with the gases inside the rotary kiln and are suitable for introduction at the main firing in the rotary kiln (GIZ/Holcim, 2020).

Substitution rate
Substitution rates of up to 20% sustainable biomass for fossil fuels in cement plants have been reported in the literature, with very few cases reporting more than 20% substitution rate (Murray and Price, 2008, Uśon et al., 2013, Rahman et al., 2015).

Technical challenges
The relatively low calorific value and relatively high moisture content of the biomass can also cause flame instability. This can be overcome by limiting the substitution rate and adjusting the air flow and the flame shape (Murray and Price, 2008). Biomass can degrade with time; thus, it should be used before it begins to break down. Newer biomass should be inserted at the bottom of the storage facility so that the oldest biomass can be used in the kiln first (Rahman et al., 2015).

Because of the increase in the potassium oxide (K_2O) content, the melting point of the ashes decreases, thus enhancing agglomeration problems in the combustion chamber, hence the co-combustion of biomass with coal or pet coke (which have lower calcium contents) at the aforementioned substitution rate is recommended. These mixtures produce ashes with a higher melting point and operational problems can thus be avoided (Uśon et al., 2013).

The halogens that may be present in some biomass can cause slagging or corrosion of the cement kiln. However, co-processing biomass with fossil fuels with higher sulfur content (e.g., coal) prevents the formation of alkaline and chlorine compounds (Murray and Price, 2008).

5.6. Chemical and Hazardous Waste

Chemical hazardous waste consists of waste such as waste oils, spent solvents, obsolete pesticides, paint residue, and anode wastes (Murray and Price, 2008). Waste oil originates from the automotive, railway, and marine industries (Rahman et al., 2015), whereas the rest of the chemical and hazardous wastes are typically the waste solvents available from the chemical and electroplating industry (Seyler et al., 2005). Waste oils and solvents typically have a high calorific value (see Figure 5) and can be used in the cement kiln at a very low cost. The use of waste solvents is especially cost-effective for the cement plants located in the vicinity of the other industrial establishments that produce waste solvents. Substitution of fossil fuels by waste oil and solvents results in the reduction of CO_2 emissions, NOx emissions, mercury, and heavy metals emissions. However, SO_2 emissions may increase as a result of waste oil and solvent burning (Rahman et al., 2015).

Fuel dosage
The feed point for liquid fuels depends on their capacity for atomization. Generally, waste oils and solvents are not pre-treated. They can be fed through primary burner as well as through the calciner using the fuel oil firing system (Rahman et al., 2015).

Substitution rate
Due to the variable characteristics of the chemical and hazardous wastes, a generalized substitution rate cannot be provided. However, substitution rates up to 57% for obsolete pesticides have been reported (Karstensen et al., 2006).

Technical challenges
Waste oils and solvents contain fewer minerals compared to conventional fossil fuels like coal and pet coke (IFC, 2017). As a result, an additional raw mill has to be used to maintain the quality of cement. Waste oils are more contaminated with sulfur, halogens, phosphorus, and heavy metals posing a technical challenge for storage due to potential environmental hazards.

6 Impact of Alternative Fuels Co-Processing in the U.S. Cement Industry

There have been myriad studies analyzing the environmental impact of use of alternative fuels in cement industry. The following section summarizes key findings of our analysis related to impact of alternative fuels on CO_2 and select non-CO_2 emissions. The impact of alternative fuels co-processing on emissions depends on the composition of alternative fuels and the source of biogenic emissions.

6.1. CO_2 Emissions Impact of Alternative Fuels

Figure 8 compares the CO_2 emissions generated by the combustion of various alternative fuels and fossil fuels to produce one GJ of energy. These emission factors form the basis of the analysis presented in this section. Generation of one GJ of energy with coal results in the highest CO_2 emissions amongst fossil fuels. Alternative fuels such as MSW and sewage sludge can generate almost similar or slightly higher CO_2 emissions to produce one GJ of energy compared to fossil fuels if their biogenic CO_2 emissions are not considered carbon-neutral. However, the entire carbon content or a fraction of the carbon content of these fuels is considered biogenic and depending on the accounting method for carbon emissions, the biogenic carbon content may or may not be considered carbon neutral.
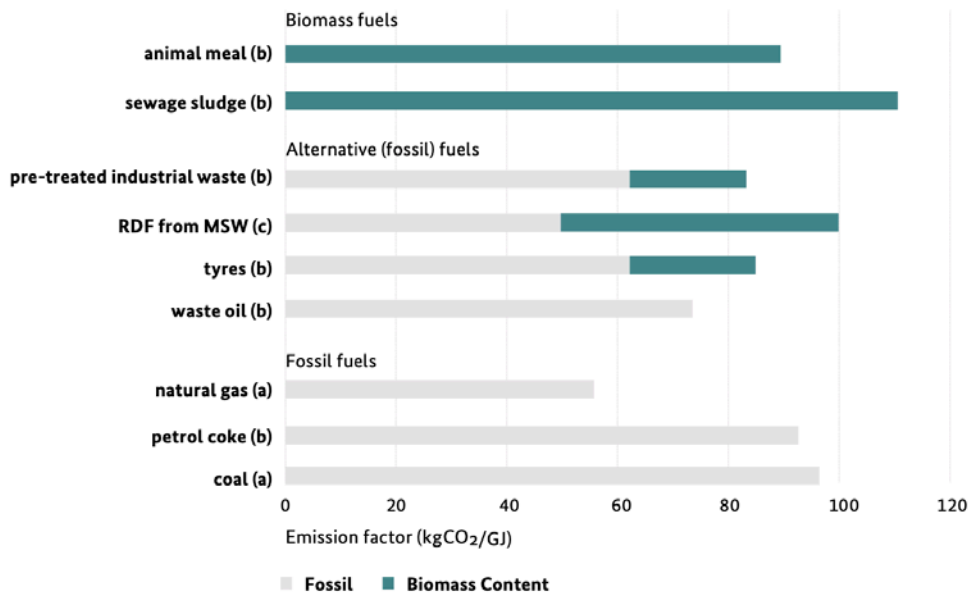
Figure 8. Comparison of typical CO_2 emission factors per GJ of energy produced for different fuels (Data sources: (a) IPCC default values, (b) CSI default value (c) CDM project; adopted from GIZ/Holcim, 2020)[4]

In order to take into account both non- biogenic and biogenic carbon emissions for alternative fuels with biogenic carbon content, Figure 9 below presents potential emissions reductions for both cases (top of shaded bars shows emissions if accounting for both biogenic and non- biogenic emissions, and top of solid bars shows emissions if only accounting for non- biogenic CO_2 emissions).

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4   Emission factors for coal and petcoke vary between the range of 87 to 101 kg CO_2/GJ and 83 to 115 kgCO_2/GJ, respectively. However, it should be noted that the emission factors used for coal, petcoke and natural gas for the analysis presented in figure 9 are adopted from EPA GHG emission factors database (EPA, 2022b).

It should be noted that the emission factors for alternative fuels such as biomass, sewage sludge and MSW can vary based on their composition. Figure 8 and subsequent analysis assumes default average values reported for the emission factors for these alternative fuels. Moreover, emission factors used in this analysis do not include the emissions caused by pre-processing and transportation of fuels.

In order to analyze the effect of the replacement of carbon-intensive fossil fuels on CO_2 and non- CO_2 emissions of the U.S. cement industry, three scenarios for replacing the most carbon-intensive fossil fuels (i.e., coal and pet coke) with alternative fuels and lower carbon fossil fuels such as natural gas are created. Figures 9 to 12 and the corresponding text present potential reductions in CO_2 and non-CO_2 emissions under three scenarios for the replacement of coal and pet coke by various alternative fuels and natural gas. First two scenarios reflect the reality by assuming overall shares of alternative fuels in total final energy demand similar to the average and maximum values from the EU countries, whereas third scenario analyzes the most ambitious case of alternative fuel substitution rates for the U.S. cement industry. The three scenarios are as follows:

> 1) 20% Replacement Scenario[5]: In this scenario, 20% of coal and pet coke from the current fuel mix (which equals 12% of total fuel mix) is replaced by alternative fuels and natural gas for the U.S. cement industry.

> 2) 50% Replacement Scenario: In this scenario, 50% of coal and pet coke from the current fuel mix (which equals 30% of total fuel mix) is replaced by alternative fuels or natural gas for the U.S. cement industry.

> 3) 100% Replacement Scenario: In this Scenario, 100% of coal and pet coke from the current fuel mix (which equals 59% of total fuel mix) is replaced with alternative fuels and natural gas for the U.S. cement industry.

Three out of five alternative fuels studied in this report have lower carbon content than the fossil fuels such as coal and pet coke (see Figure 4) on a weight basis. Replacement of coal or pet coke with these alternative fuels can potentially lower the energy-related CO_2 emissions from the cement production. However, as their calorific values are lower than those of fossil fuels (see Figure 5), larger quantities of alternative fuels are burned in order to produce the equivalent amount of energy for clinker production. As a result, emissions reductions are relatively marginal in most cases, especially if biogenic CO_2 emissions are not considered carbon-neutral.

Total CO_2 emissions considered in this study include both energy-related and process-related emissions from the U.S. cement industry. The energy-related CO_2 emissions are estimated based on the fuel consumption data obtained from USGS (USGS, 2022) and CO_2 emission fac- tors adopted from GIZ/Holcim report (see figure 8) and EPA´s GHG emission factors database (EPA, 2022b), whereas the process-related CO_2 emissions are estimated based on the pro- cess-related CO_2 emission factor for clinker (Hasanbeigi et al., 2019) and clinker production in the U.S. cement industry (USGS, 2022). Co-processing of sewage sludge (accounting for both biogenic and non- biogenic carbon emissions) and waste oil & solvents represent the largest CO_2 emissions reduction potential for the U.S. cement industry. Under the 20% Replacement Scenario, sewage sludge and waste oil & solvents can potentially reduce about 1% of current total CO_2 emissions, whereas the abatement potential increases to about 4% of current total CO_2 emissions in the 50% Replacement Scenario and 7% in the 100% Replacement Scenario if biogenic CO_2 emissions are not considered carbon-neutral.

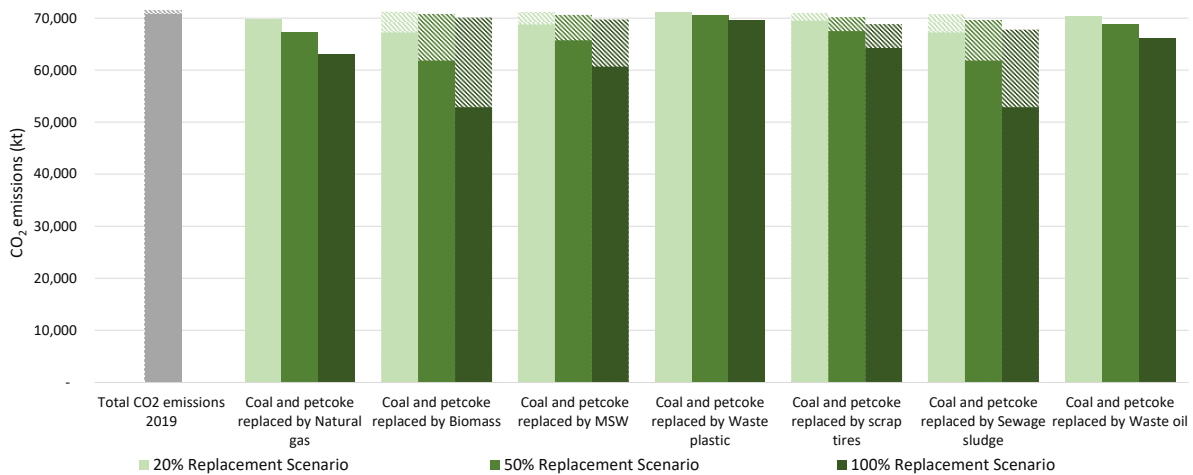5   The resulting fuel mix is presented in appendix 3

Figure 9. Annual total CO_2 emissions (energy-related + process-related) after replacing 20%, 50% and 100% of coal and pet coke with various alternative fuels and natural gas in the U.S. cement industry in 2019 (Source: this study).

Note: Note: the shaded part of the bars indicates the share of CO_2 emissions that are biogenic.

Co-processing of scrap tires (accounting for both biogenic and non-biogenic carbon emissions) can potentially reduce 1%, 2% and 4% of current total CO_2 emissions from the U.S. cement industry across all three scenarios. Waste plastic co-processing represents 1% CO_2 emissions reduction potential in 20% Replacement Scenario and 50% Replacement Scenario each, which increases to 3% under 100% Replacement Scenario. It should be noted that due to its high chlorine content, the waste plastics replacement ratio is typically kept below 5%.

Co-processing of MSW (accounting for both biogenic and non- biogenic carbon emissions) can potentially result in 0.5%, 1% and 2% of current total CO_2 emissions reduction across three scenarios. Replacing 20% of coal and pet coke with biomass (accounting for biogenic carbon emissions) can potentially reduce approximately 0.4% of current total CO_2 emissions; replacing 50% of coal and pet coke with biomass can potentially reduce 1% of total CO_2 emissions, and replacing entire share of coal and pet coke with biomass can reduce about 2% of U.S. cement industry's current total CO_2 emissions. Net biogenic carbon emissions can vary considerably depending on the biogenic source and therefore, a specific assessment of each individual fuel is necessary to conclude whether the biogenic content can be considered carbon neutral. In those cases where the assessment shows that the biogenic content can be considered carbon neutral, the emissions benefit from replacing coal and pet coke with such fuel is considerably higher.

Replacing 20% of coal and pet coke from the current fuel mix with natural gas will potentially result in 2% reduction in the total CO_2 emissions, and replacing 50% of coal and pet coke from the current fuel mix with natural gas will potentially result in 6% reduction in the total CO_2 emissions compared to the current emission levels; whereas, replacing 100% coal and pet coke with natural gas can potentially reduce about 12% of current total CO_2 emissions from the U.S. cement industry.

6.2. Non-CO$_2$ Emissions Impact of the Alternative Fuels

Alternative fuels discussed in this report typically contain sulfur, nitrogen, heavy metals, and chlorine (see Figure 4), which, upon combustion can form air pollutants such as SO_2, NO_x, dioxins and furans, and heavy metals. The following section presents the quantitative impact

of switching from fossil fuels to alternative fuels on SO_2, NOx, and Particulate matter (PM) emissions from the U.S. cement industry. A qualitative analysis based on the literature survey is also presented for the pollutants where quantitative analysis was not possible due to the lack of data. The non- CO_2 pollutants included in this study are selected based on their importance emphasized throughout the literature and data availability. The non-CO_2 pollutants analysis presented here is not exhaustive and there are numerous pollutants of concern related to some alternative fuels, like per-and-poly-fluoro alkyl substances (PFAS) in MSW and waste plastic, which have not been evaluated in this report due to lack of available data.

Sulfur dioxide (SO_2) emissions
Sulfur compounds present in raw materials as well as in the fuel result in the formation of SO_2. Due to the highly alkaline environment in the cement kiln, the majority of SO_2 formed is directly absorbed into the product resulting in the mitigation of SO_2 emissions from the exhaust stream (EPA, 2022; European Commission, 2013). Although the sulfur content of some alternative fuels is lower than that of conventional fuels on weight basis, co-processing of some alternative fuels increases total SO_2 emissions because of larger quantities of alternative fuels required to produce energy equivalent to the combustion of fossil fuels.

Total SO_2 emissions are estimated based on the fuel consumption reported by USGS and emission factors from EPA and EEA (EPA, 2020b; EMEP/EEA, 2019)[6]. Sewage sludge represents the largest potential for the reduction of SO_2 emissions from the U.S. cement industry (Figure 10). Replacing coal and pet coke with waste plastic can potentially result in the largest reduction of SO_2 emissions from the U.S. cement industry, from 16% reduction in current SO_2 emissions for 20% replacement scenario to 82% reduction of current SO_2 emission levels in 100% replacement scenario.

Co-processing of sewage sludge in the 20% Replacement Scenario can potentially reduce 16% of current SO_2 emissions; in the 50% Replacement Scenario, it can potentially result in 26% reduction in current SO_2 emissions, and in the 100% Replacement Scenario, it can potentially reduce about half of the current SO_2 emissions from the U.S. cement industry. Waste oil co-processing represents about 10% SO_2 emissions reduction potential for the 20% Replacement Scenario, about 24% SO_2 emissions reduction potential for the 50% Replacement Scenario, and 48% SO_2 emissions reduction potential for the 100% Replacement Scenario.

Biomass co-processing in the 20% Replacement Scenario can potentially reduce about 4% of the cement industry's current SO_2 emissions; in the 50% Replacement Scenario, biomass co-processing can reduce about 9% of SO_2 emissions, and in the 100% Replacement Scenario, biomass co-processing can potentially reduce about 18% SO_2 emissions. Co-processing with scrap tires can potentially result in a marginal increase in the total SO_2 emissions from the cement industry by approximately 1%, 2%, and 4% across three scenarios, respectively, whereas co-processing with MSW has a negligible effect on the total SO_2 emissions from the U.S. cement industry. Replacing coal and pet coke with natural gas in the current fuel mix can potentially result in SO_2 emissions reductions of 15%, 38%, and 76% across three scenarios, respectively.

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6   EEA and EPA emission factor databases provide emission factors for waste incineration. The emission factors for incinerators reported as pollutant emissions per tonne of waste with abatement technologies are converted to emission factors per GJ of energy produced using the heating values provided by EPA (EPA, 2022).
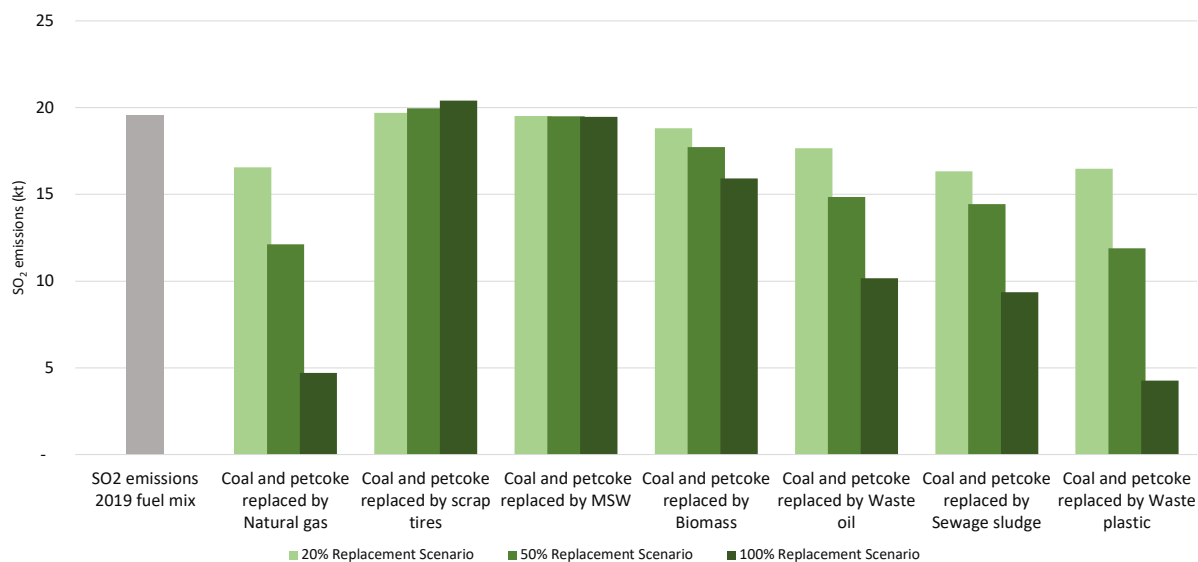
Figure 10. Annual energy-related SO_2 emissions after replacing 20%, 50% and 100% of coal and pet coke with various alternative fuels and natural gas in the U.S. cement industry in 2019 (Source: this study).

Nitrogen Oxides (NO$_x$) emissions

Chemically bound nitrogen from the fuels is oxidized at a high temperature to form various oxides of nitrogen (NO and NO_2 are the most dominant oxides). Waste fuels with more nitrogen content will result in higher NO$_x$ formation. However, NOx formation from primary firing can be lower if the waste fuels contain water or need excess oxygen, which results in a lower flame temperature. This can have an effect similar to the NOx emissions control technique of flame cooling. If waste fuel used is coarser, the NOx formation in pre-calciner is lower (European Commission, 2013).

Total NOx emissions are estimated based on the fuel consumption reported by USGS and emission factors from EPA and EEA (EPA, 2020b; EMEP/EEA, 2019). Co-processing of sewage sludge and waste oils & solvents in cement kilns represents the largest potential for NOx emissions reduction (Figure 11). In the 20% Replacement Scenario, sewage sludge and waste oils & solvents co-processing represents about 17% NOx emissions reduction potential, which increases to 44% in 50% Replacement Scenario and about 87% of current NOx emissions in the 100% Replacement Scenario. Co-processing of MSW and waste plastic can potentially reduce about 14% of current NOx emissions in the 20% Replacement Scenario, about 35% of current NOx emissions in the 50% Replacement Scenario, and about 70% % of current NOx emissions in the 100% Replacement Scenario. Scrap tires co-processing can potentially reduce 10%, 25% and 49% of current NOx emissions across all three scenarios. Co-processing of biomass represents the lowest potential for NOx emissions reduction: 5% potential for NOx emissions reduction in the 20% Replacement Scenario, 14% potential for NOx emissions reduction in the 50% Replacement Scenario, and about 27% NOx emissions reduction potential in the 100% Replacement Scenario. Replacing 20% of coal and pet coke from the current fuel mix with natural gas will potentially result in 15% reduction in NOx emissions, and replacing 50% of coal and pet coke from the current fuel mix with natural gas will potentially result in 38% reduction in NOx emissions; whereas replacing the entire share of coal and pet coke with natural gas can potentially reduce about 86% of NOx emissions compared to the current emission levels.
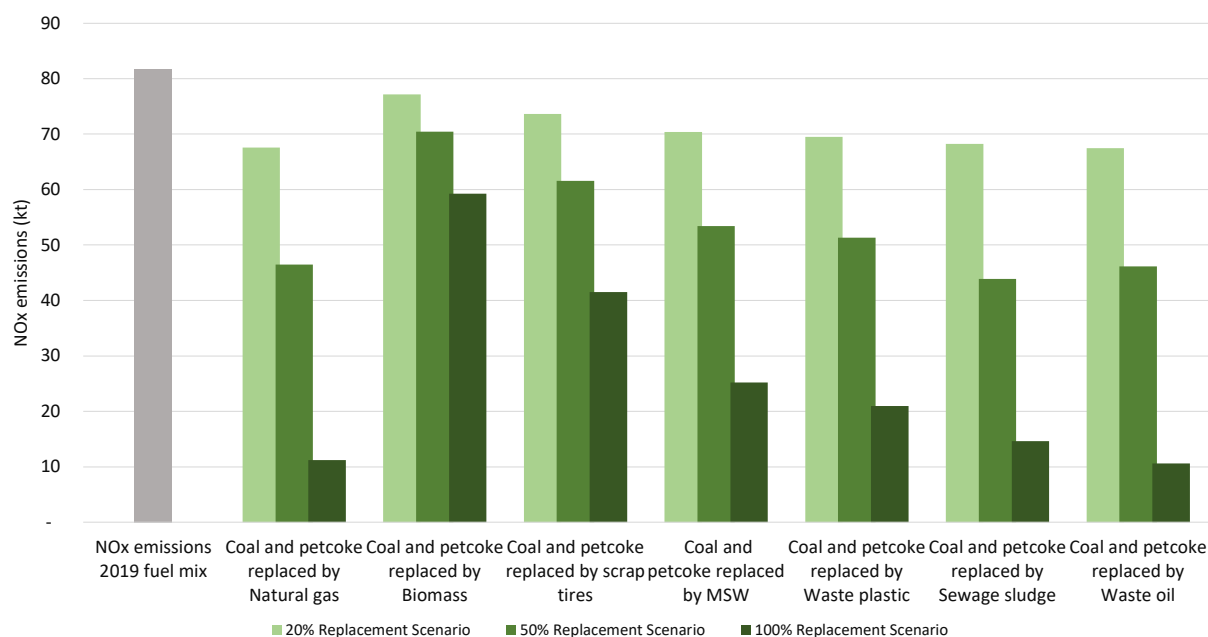
Figure 11. Annual energy-related NOx emissions after replacing 20%, 50% and 100% of coal and pet coke with various alternative fuels and natural gas in the U.S. cement industry in 2019 (Source: this study).

Particulate matter (PM) emissions

Co-processing sewage sludge represents the largest PM emissions abatement potential for the U.S. cement industry (Figure 12). Sewage sludge co-processing can potentially reduce 13% of current PM emissions in the 20% Replacement Scenario, 28% of current PM emissions in the 50% replacement scenario and 55% of current PM emissions from the U.S. cement industry in the 100% Replacement Scenario. Co-processing of MSW and biomass both represent PM emissions reduction potential of about 10%, 20%, and 40% of current emission levels across three scenarios for the U.S. cement industry. Co-processing waste oil represents about 9% of PM emissions reduction potential in the 20% Replacement Scenario, which increase to 12% for the 50% Replacement Scenario, and 25% of current PM emissions for the 100% replacement scenario for the U.S. cement industry. Co-processing of scrap tires in the cement kiln represents the lowest potential for PM emissions reduction, 8% ,9%, and 18% emissions reduction potential under the 20% Replacement Scenario, 50% Replacement Scenario, and 100% Replacement scenario, respectively.

Replacing coal and pet coke with waste plastic can potentially result in largest reduction of PM emissions from the U.S. cement industry, from 15% reduction in current PM emissions for 20% replacement scenario to 75% reduction of current SO_2 emission levels in 100% replacement scenario. Replacing 20% of coal and pet coke from the current fuel mix with natural gas will potentially result in 13% reduction in PM emissions, replacing 50% of coal and pet coke from the current fuel mix with natural gas will potentially result in 30% reduction in PM emissions, and replacing the entire share of coal and pet coke with natural gas will potentially result in 61% reduction in PM emissions compared to the current emission levels.
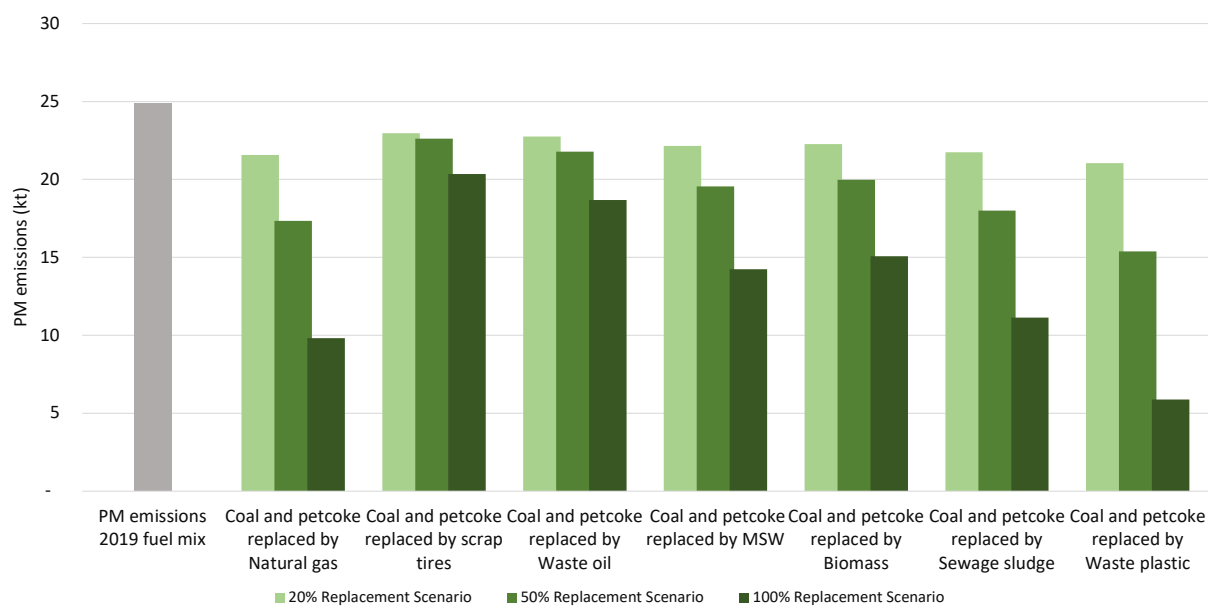
Figure 12. Annual energy-related PM emissions after replacing 20%, 50%, and 100% of coal and pet coke with various alternative fuels and natural gas in the U.S. cement industry in 2019 (Source: this study).

Dioxins and furans emissions (PCDD/PCDFs)
The PCDDs and PCDFs can form because of a combination of formation mechanisms depending on the kiln and process configuration, combustion conditions, and feed characteristics (Karstensen, 2008). Typically, PCDDs and PCDFs form if chlorine is present in the fuels or raw materials. High residence times and high temperatures can help to reduce the PCDD/PCDF formation (Zemba et al., 2011). Various alternative fuels are fed at different locations. While the fuels fed in the main firing system can reach high enough temperatures and residence times to limit the PCDD/PCDF formation, fuels fed to the secondary firing system may not reach the temperatures and residence times high enough to curtail the PCDD/PCDF formations (Hasanbeigi et al., 2012). However, replacing fossil fuels with alternative fuels has a limited effect on PCDD/PCDF emissions of the cement kiln (Karstensen, 2008). While for the co-processing of sewage sludge the dioxins and furans emissions remain unchanged, for co-processing of all other alternative fuels, the dioxins and furans emissions marginally decrease (Murray and Price, 2008; Uśon et al, 2013; Carrasco et al., 2002; PCA, 2008; European Commission, 2013).

Heavy metals emissions
Heavy metal particles are typically found in the cement kiln dust. Their concentration depends on the feedstock, fuels, and recirculation in the kiln system. The use of waste fuels in particular can increase the concentration of heavy metals in the clinker process (UNEP, 2008). Non-volatility of the heavy metals allows them to pass directly through the kiln system and be incorporated in the clinker. The volatile heavy metals introduced with the alternative fuels are partly recycled inside the kiln and some small portions are emitted with the exhaust gas. Emissions of highly volatile heavy metals such as Thallium, Mercury, Cadmium, Lead, Selenium and their compounds go up due to the co-processing of alternative fuels.

These heavy metals and compounds leave the kiln system along with the dust, which can be controlled using dust control devices. The co-processing of MSW results in an increase in the heavy metals emissions from the cement kiln. Co-processing of sewage sludge does not

result in a significant change in the heavy metals emissions, whereas co-processing of waste tires, biomass, and waste solvents results in the marginal reduction of heavy metals emissions from the cement kiln (Rahman et al., 2015; Murray and Price, 2008; Uśon et al, 2013; Carrasco et al., 2002; PCA, 2008; European Commission, 2013).

6.3. Impact of Alternative Fuels on Product Quality and Process

Alternative fuels need different ignition temperatures and air requirements, thus altering the chemistry of the kiln system. The ashes produced during the combustion process and the volatile components from the fuels get entrapped in the crystal lattice of the clinker phase. The composition of ashes and the quantity of volatile components depend on the type of fuel used in the cement kiln. Thus, the use of alternative fuels for co-processing may lead to the modification of clinker properties (Chatterjee and Sui, 2019). Due to their lower calorific values, the alternative fuels reduce the peak temperature of the fuel and lengthen the flame resulting in changes of the clinker microstructure. The microstructural changes may lead to deterioration in the grinding characteristics and lower the strength of the resultant cement (Chatterjee and Sui, 2019). Co-processing of alternative fuels can lead to higher concentrations of alkalis (K_2O, Na_2O). High levels of alkali in the presence of moisture can lead to the production of gel which expands and give rise to cracking in concrete and mortars (Chinyama, 2011).

The co-processing of alternative fuels in the kiln results in modifications of certain process conditions and as a result, modification of clinker properties. The co-processing of alternative fuels can potentially lead to the formation of volatile cycles in the preheater kiln section due to the reaction between chlorine, sulfur and alkali. The presence of water vapor, chlorine, sulfur and alkali can lead to the formation of free CaO making it difficult to achieve complete conversion of lime. The presence of fluorine and dissociated radicals alter the viscosity and surface tension of clinker melt. A high concentration of chlorine in the kiln system can cause very high recirculation load and clogging of the preheater and can lead to the modification of clinker phase properties (Chatterjee and Sui, 2019).

In case of incomplete combustion of the fuel in the main burner or pre-calciner, they burn with the bed material of a rotary kiln, which leads to the formation of local reducing conditions and an increase in the local circulation of sulfur, chlorine, sodium and potassium. The use of alternative fuels can especially result in the higher internal circulation of volatile inorganic substances. The increased internal circulation of volatile inorganic substances can lead to material build-ups, blockages, ring formation, and shell corrosion, causing unstable process, low clinker production and high heat consumption. Thus, the co-processing of alternative fuels in the cement kiln, if not done properly, can result in a considerable energy penalty (Cortana Mut et al., 2015). Moreover, as a result of additional energy consumed for the pre-treatment of alternative fuels, energy intensity for overall cement production will likely increase.

6.4. Co-Benefits of Co-Processing Alternative Fuels in the Cement Industry

Along with reducing CO_2 emissions, substituting fossil fuels with alternative fuels has several co-benefits, such as the recovery of the energy content of waste, lowering cement production costs in some cases, and reducing waste sent to landfills. The following section briefly discusses a few co-benefits of co-processing alternative fuels in the cement industry.

Minimization of landfills and dedicated incineration

Large amounts of industrial and domestic waste materials are generated every year. For example, In the U.S. alone, about 4.4 Mt of scrap tires (About 24% used as fuel in cement plants (U.S. Tire manufacturer association, 2020)), 35 Mt of hazardous waste (EPA, 2021), and 292 Mt of MSW (including plastic; EPA, 2022a) is generated every year. Currently, about 25% of scrap tires in the US are disposed of in landfills or incinerators, and about 50% of municipal waste is sent to landfills. The utilization of the waste materials in the existing cement plants can thus be beneficial by reducing the need for new investments for waste disposal, such as secure landfill sites or new incinerators (ECRA, 2016).

Safe disposal of hazardous waste

Hazardous waste pollutes both land and groundwater and may pose risks to human health. Some industrial wastes such as obsolete pesticides, spent solvents, anode wastes have high concentrations of heavy metals, and their elimination is problematic and expensive. The high temperatures in cement kilns and the residence times are comparable to modern incinerators. Moreover, the kiln operates in an oxidizing and alkaline environment, thus making them more environmentally sound and cost-effective option for the disposal of hazardous waste (Zhu, 2011; IFC, 2017; GIZ/Holcim, 2020).

However, any co-processing of hazardous waste in cement plants should be done under strict technical, health, and environmental control protocols. It is mandated in the U.S. to perform a test burn for the hazardous waste co-processing in the cement kiln to demonstrate the combustion performance. In order to get approval for hazardous waste co-processing in the U.S, the cement plant has to demonstrate the destruction and removal efficiency of more than 99.9% for principal organic hazardous compounds in the hazardous waste materials (GIZ/Holcim, 2020).

7 Emission Control Technologies

According to the U.S. Environmental Protection Agency (EPA) exposure to air pollutants such as SO_2, NOx, and PM can cause a variety of respiratory health effects, including inflammation of the lining of the lungs, reduced lung function, and respiratory symptoms, increased susceptibility to respiratory infection, premature mortality, aggravation of cardiovascular disease, decreased lung function growth, exacerbation of allergic symptoms, neurodevelopmental effects such as lowered IQ and behavioral problems, reduction in the capacity of the blood to carry oxygen, thereby decreasing the supply of oxygen to tissues and organs such as the heart, and many other negative health effects (U.S. EPA, 2015).

Air pollutants originating from Portland cement manufacturing facilities in the U.S. are regulated under the programs such as National Emissions Standards for Hazardous Air Pollutants (NESHAP), Clean Air Act (CAA) and National Air Ambient Air Quality Standards (NAAQS). Numerical limits on the air pollutant emissions proposed by the United State EPA are presented in Table 7 below. To comply with these regulations, emissions of air pollutants from cement plants can be controlled by various primary and secondary techniques either by limiting the formation of pollutants in the first place or by capturing the pollutants from the exhaust gas or by combination of both. The following section presents a brief description along with the efficacy of commercially available technologies that can be implemented to control the emissions of air pollutants.

Table 7. Emission limits for air pollutants from cement manufacturing in the U.S under CAA and NAAQS.

Pollutant	Limit	Unit	Source
NOx	2.3 to 4	lb/ t-clinker	EPA, 2022b
PM	0.02 to 0.07	lb/t-clinker	EPA, 2018

7.1. Nitrogen Oxide (NOx) Emissions Control Techniques

The majority of alternative fuels contain nitrogen in various proportions ranging from 1% in waste fuels to about 24% in waste tires. High temperature in the kiln causes the oxidation of chemically bound nitrogen in the fuel leading to formation of oxides of nitrogen (NOx) (EPA, 2020). NOx emissions can be controlled by either reducing its formation by optimizing or modifying the kiln parameters or the shares of waste raw materials and waste fuels or by capturing the NOx from the flue gases. The reduction or control of NOx emissions can be done using primary or secondary methods (European Commission, 2013). Table 8 provides brief descriptions for the primary and secondary methods to reduce and control NO_x emissions.

Table 8. Brief description of NOx emissions reduction or control methods (European Commission, 2013).

Control technique	Description	Abatement efficiency
Flame cooling	Water or water and compressed air are added to the flame to lower the temperature and thus reduce the formation of NOx.	Up to 35%
Low NOx burners	These burners are designed to operate with the reduced air requirement thus causing early combustion of volatile compounds and reducing the NOx formation.	Up to 35%
Mid-kiln firing	Mid-kiln firing systems are installed on the long kiln to create reducing zones by introducing lump fuels which results in reduction of NOx emissions.	20-40%
Mineralized clinker	Addition of mineralizers such as fluorine reduces the temperature of sintering zone thus helping to reduce the NOx formation.	10-15%
Staged combustion	Typically applied to kilns with pre-calciner. The first stage consists of clinker burning under optimum conditions followed by the second stage consisting of a reduction zone where a portion of NOx is decomposed.	10-50%
Selective non-catalytic reduction (SNCR)	SNCR involves introduction of ammonia water, ammonia precursor or urea solution in the combustion gas at the temperatures between (800°C to 1000°C) to reduce NO to N_2 thus reducing the formation of NOx.	30-90%
Selective catalytic reduction	SCR includes introduction of ammonia along with the catalyst at 300°C to 500°C to reduce NO or NO_2 to N_2.	85-95%

7.2. Sulfur dioxide (SO_2) emissions control techniques

SO_2 is primarily generated from the oxidation of sulfur compounds present in the alternative fuels. The percentage of sulfur in some selected alternative fuels is presented in Figure 4. Emission of SO_2 can most effectively be controlled by process optimization techniques such as clinker burning process, raw material distribution in the kiln riser or controlling the oxygen concentration in the kiln inlet area (European commission, 2013). There are several end-of-pipe techniques implemented along with the process optimization to control SO_2 emissions. Table 9 below presents a brief summary of control techniques available for the reduction of SO_2 emissions from the cement manufacturing facility.

Table 9. Brief description of SO_2 emissions reduction or control methods (European Commission, 2013).

Control technique	Description	Reduction efficiency
Absorbent addition	Absorbents such as slaked lime ($Ca(OH)_2$), quicklime (CaO) or activated fly ash with high CaO content can be added to exhaust gas to absorb the SO_2.	60-80%
Wet scrubber	A slurry of absorbent like calcium carbonate is sprayed in the spray tower where SO_2 is absorbed from the flue gases.	90%
Activated carbon	Activated carbon can either be injected or constructed as a packed bed which then acts as an adsorbent for SO_2 as well as several other pollutants such as organic compounds, metals, NH_3, NH_4, HCL, HF and residual dust.	Up to 95%
Dry scrubber	A blend of slacked lime and raw meal is fed to a venturi reactor column where it forms a fluidized bed and intensive contact between the solid and the gas results in SO_2 absorption.	90%

7.3. Particulate Matter (PM) Emissions Control Techniques

Although the substitution of fossil fuels with alternative fuels does not have a significant effect on the PM emissions that take place from kiln systems and kiln coolers, the fugitive PM emissions can be controlled using electrostatic precipitators (ESPs) or fabric filters. ESPs control the PM emissions by generating an electrostatic field across the path of particulate matter in the air stream. This causes the particles to get negatively charged and then they are collected at the positively charged collection plates. Fabric filters typically use semi-permeable fabric membranes to filter out particulate matter. The efficiency of ESPs varies depending on the operating stages. ESPs are less efficient during startups and shutdowns, whereas fabric filter efficiency is unaffected (European Commission, 2013).

7.4. Dioxins and Furans Emissions Control Techniques

Dioxins and furans (PCDDs /PCDFs) emissions can be controlled by minimizing their formation through primary techniques like kiln optimization, minimizing fuel use, and careful selection of fuels and raw materials. The possibility of PCDD and PCDS reformation can be minimized by quick cooling (below 200°C) of exhaust gas, not using waste fuels during startup or shutdown, monitoring critical process parameters, and avoiding fuels with high halogen contents (European commission, 2013). Adsorption on activated carbon is also a proven technique in other sectors to mitigate the emissions of PCDD/PCDFs (Zemba et al., 2011).

8 Conclusions

This study investigates the CO_2 and select non-CO_2 emissions impact of co-processing alternative fuels in the U.S. cement industry. The report also presents a summary of the most widely used alternative fuels in the U.S. cement industry along with their typical substitution rate, dosage systems, and technical challenges in their co-processing. In this study, we investigate the impact of co-processing of the following alternative fuels in the U.S. cement industry: Scrap tires, waste plastic, municipal solid waste, waste oil, sustainable biomass, and sewage sludge.

Based on our quantitative analysis, the impact of the co-processing of alternative fuels on CO_2 emissions was marginal for most of the alternative fuels, especially if biogenic CO_2 emissions are not considered carbon-neutral. The co-processing of waste oils and solvents has the maximum potential for reducing CO_2 emissions from the U.S. cement industry, followed by sewage sludge, scrap tires, and waste plastic. MSW and biomass represent the lowest CO_2 abatement potential for co-processing in the U.S. cement industry; with the exception of narrow biomass sources, carbon neutrality of the biogenic content can reasonably be assumed. Replacing coal and pet coke with natural gas represents larger potential than alternative fuels co-processing for CO_2 emissions reduction in the U.S. cement industry.

Although the CO_2 emissions from a cement plant can potentially be reduced with the co-processing of alternative fuels, in some cases, the emissions of non-CO_2 air pollutants can increase. Based on the impact analysis of non-CO_2 emissions, the SO_2 emissions from the U.S. cement industry increase for the coal replacement by scrap tires and municipal solid waste, and marginal reduction is observed for biomass and waste oil. Co-processing by sewage sludge represents the most considerable potential for SO_2 emissions reduction from the U.S. cement industry.

Coal replacement by all alternative fuels can potentially reduce NOx emissions from the U.S. cement industry. Co-processing of waste oil represents the largest NOx reductions potential, followed by sewage sludge, municipal solid waste, and scrap tires; the co-processing of biomass represents the lowest potential for NOx emissions reduction from the U.S. cement industry. Although the particulate matter emissions from the co-processing of all alternative fuels can result in lower emissions, the total reduction potential is not significant. Similar to CO_2 emissions, replacing coal and pet coke with natural gas can potentially have bigger impact on the reduction of non-CO_2 emissions from the U.S. cement industry.

According to our assessment based on the literature survey, the emissions of PCDDs/PCDFs and heavy metals marginally reduce or remain unchanged for the co-processing of alternative fuels in the cement industry.

Apart from the impact on CO_2 and non-CO_2 emissions, the introduction of alternative fuels can increase the quantity of volatile inorganic substances in the kiln system, thus, leading to changes in kiln chemistry and modifications of the clinker property.

Air pollutants such as SO_2, NOx, and PM can cause severe damage to human health. Thus, it is imperative to eliminate or control the emissions of air pollutants from cement manufacturing.

The emissions of air pollutants can be controlled by either limiting the formation of pollutants by various primary techniques or by capturing the emissions by secondary techniques. Primary techniques typically include techniques such as optimizing the kiln parameters and modifying the shares of waste materials or waste fuels for PCDDs/PCDFs emissions reduction, flame cooling and mid-kiln firing for NOx emissions reduction, and controlling oxygen concentration at the kiln inlet area, and distribution of raw material in the kiln riser for SO_2 emissions reduction. The secondary techniques include techniques such as catalytic reduction for NOx emissions, wet or dry scrubbers and activated carbon for SO_2 emissions, and electrostatic precipitators and fabric filters for particulate matter. The combination of primary and secondary techniques can potentially achieve reduction efficiencies up to 95%.

Substituting conventional fossil fuels with alternative fuels can possibly have other benefits, such as safe treatment of hazardous waste and minimization of waste disposal through waste disposal incineration or landfills. However, the co-processing of alternative fuels, especially waste-derived fuels, in the cement industry will not result in a meaningful reduction in the overall CO_2 emissions of the cement industry, especially if biogenic CO_2 emissions are not considered carbon-neutral. Depending on the fuel used, co-processing of alternative fuels in cement plants can lead to emissions of other chemicals like VOCs and PFAS not studied in this report, which can cause negative environmental and health impacts to local communities.

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Appendices

Appendix 1. Boundaries and Methodology

More than 99% of GHG emissions from cement manufacturing are comprised of CO_2 (Hasanbeigi et al., 2019). Emissions related to process, fuels consumption, and electricity consumption contribute to total CO_2 emissions from cement manufacturing. These emissions can be attributed to either direct emissions i.e., emissions caused by the sources owned and operated by the company or indirect emissions i.e., emissions as consequence of the activities of cement manufacturing company but caused at the sources owned and operated by a different company. The CO_2 emissions from cement plants are reported for three different boundaries categorized as scope 1, scope 2, and scope 3. The CO_2 emissions can be reported based on either per tonne of clinker or cement produced. The boundaries and methods used for the CO_2 emissions analysis in the cement industry are shown in Figure A.1 and explained below.
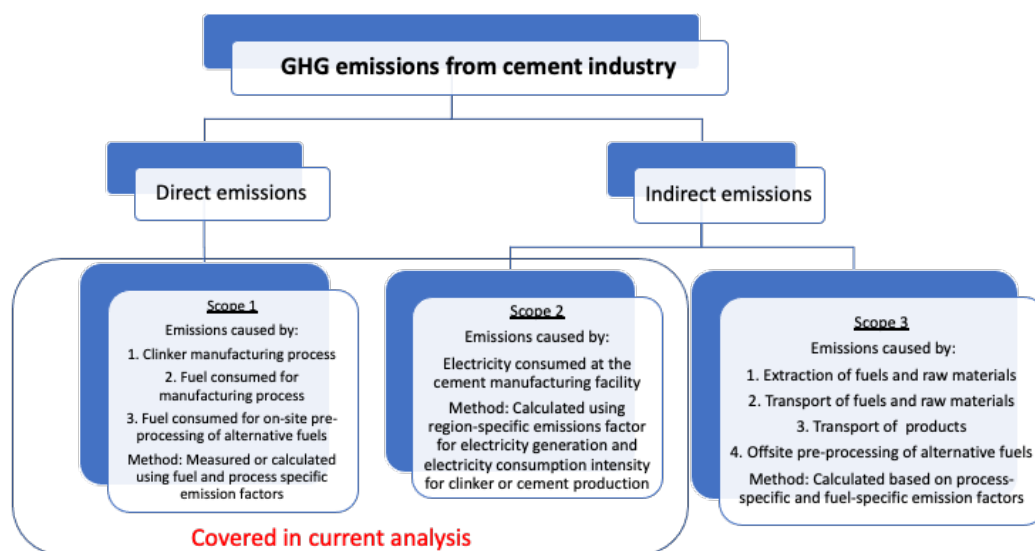

Figure A1. Boundaries and methods used for CO_2 emissions analysis in the cement industry (WBCSD, 2011)

Scope 1
Emissions generated on the industrial site by the direct sources (e.g., cement kiln) that are owned and operated by the company are accounted for under scope 1 emissions. The scope 1 CO_2 emissions consists of the process-related emissions and emissions caused by fuel combustion on site.

The scope 1 CO_2 emissions are either measured or calculated for a particular cement production facility. The emissions are calculated based on the default or region-specific emissions factors for fuel combustion and default or technology-specific emissions factors for process-related emissions.

Scope 2
The indirect CO_2 emissions generated as a result of electricity consumed at the industrial site by the equipment owned and operated by the company are accounted for under scope 2. The scope 2 emissions for the cement manufacturing are calculated based on the region or

country specific CO_2 emissions factor for the electricity generation (e.g., kg-CO_2/kWh electricity generated) and electricity consumption intensity based on the clinker or cement production (e.g., kWh electricity consumed/tonne of clinker or cement produced).

Scope 3
The indirect CO_2 emissions caused by the fuel or raw materials consumed in the cement manufacturing but generated at the sources that are not owned or operated by the company are included under scope 3. These emissions typically comprise of the emissions from activities such as extraction and production of purchased materials and fuels, transport of purchased materials and fuels, and use of sold products and services.

The scope 3 emissions are typically calculated using the LCA method or calculated based on the process specific emissions factors.

Boundaries used in this study
The current analysis covers scope 1 and scope 2 CO_2 emissions for the U.S. cement industry. As the process-related CO_2 emissions will remain unchanged for co-processing of alternative fuels, only the fuel combustion-related emissions (scope 1) are analyzed in this report. The emissions from the sources such as cement kiln for clinker production and pre-processing for alternative fuels which takes place onsite (e.g., drying, pre-combustion, gasification, hydrothermal carbonization, etc.; ECRA, 2016) are considered as scope 1 emissions for the current analysis. The CO_2 emissions for the fuel combustion in the cement kiln and for pre-processing are calculated based on default emission factors for the fuels consumed in the U.S. cement industry (EPA, 2022b) and are based on the clinker production.

Appendix 2. Pre- and Co-Processing Costs for Alternative Fuels

The use of alternative fuels in cement industry requires additional pre-processing to make them suitable for co-processing in cement kiln. In addition, the fuel feeding systems for the cement kiln need some modifications for co-processing of AFs. Table A1 presents estimates of additional costs needed for pre- and co-processing of AF in cement industry.

Table A1. CAPEX and OPEX for alternative fuel pre- and co-processing in cement plants (GIZ/Holcim 2020, ICF 2017)

Alternative fuel	Process	CAPEX	OPEX (per tonne)
Waste oils and solvents	Pre- and co-processing	$1 million to $4.8 million	$10 to $32
Scrap tires	Pre-processing	Approx. $1 million	$24 to $64
Scrap tires	Co-processing	$1 million to $4.8 million	$10 to $32
MSW	Pre- and co-processing	$ 8 million to $80 million	$16 to $64
Biomass	Pre-processing (HTC)	Approx. $45 million	Approx. $33

Table A2. Nominal prices of conventional and alternative energy carriers for U.S. cement industry in 2021

Energy carrier type	Energy carrier	Energy price (US$/GJ)	Reference
Conventional	Petcoke	10.3	GIZ/Holcim, 2020
Conventional	Natural gas	5.1	EIA, 2022
Conventional	Coal	2.7	EIA, 2022
Conventional	Fuel oil	7.1	EIA, 2022
Conventional	Electricity	21.9	EIA, 2022
Alternative	Scrap tires	0.1 to 0.2	USTires, 2021
Alternative	MSW	0.2 to 0.8	GIZ/Holcim, 2020
Alternative	Biomass	7 to 9.2	Gonzalez et al., 2011
Alternative	Waste oil	10.0	EIA, 2022

Appendix 3. Scenario Description

The impact of the co-processing of alternative fuels on CO_2 and non-CO_2 emissions is analyzed for three scenarios. First two scenarios reflect the reality by assuming overall shares of alternative fuels in total final energy demand similar average and maximum values from the EU countries, whereas third scenario analyses the most ambitious case of alternative fuel substitution rates for the U.S. cement industry. In the first scenario, 20% of coal and pet coke is replaced by alternative fuels and natural gas. The resulting fuel mix is presented in table A3. In the second scenario, 50% of coal and pet coke from cement industry's current fuel mix is replaced by alternative fuel and natural gas. The resulting fuel mix is presented in table A4. In the second scenario, the entire share of coal and pet coke from the cement industry's current fuel mix is replaced by alternative fuel and natural gas. The resulting fuel mix is presented in table A5. The shaded cells indicate the fraction of the resulting mix covered by the alternative fuel whose use is increased in each case. For example, if 20% of coal and pet coke is replaced by natural gas the resulting mix would be comprised of 37% natural gas (up from 25% in the baseline mix) and 47% coal and pet coke (down from 59% in the baseline mix).

Table A3. Resulting fuel mix from 20% replacement scenario

Fuels	Baseline	20% of coal and pet coke replaced with:					
		Natural gas	Scrap tires	MSW	Waste oils & solvents	Biomass	Sewage sludge
Coal	39%	31%	31%	31%	31%	31%	31%
Pet coke	20%	16%	16%	16%	16%	16%	16%
Oil	0%	0%	0%	0%	0%	0%	0%
Natural gas	25%	37%	25%	25%	25%	25%	25%
Scrap tires	3%	3%	15%	3%	3%	3%	3%
MSW	3%	3%	3%	15%	3%	3%	3%
Waste oils & solvents	9%	9%	9%	9%	21%	9%	9%
Biomass	0%	0%	0%	0%	0%	12%	0%
Sewage sludge	0%	0%	0%	0%	0%	0%	12%

Table A4. Resulting fuel mix from 50% replacement scenario

Fuels	Baseline	50% of coal and pet coke replaced with:					
		Natural gas	Scrap tires	MSW	Waste oils & solvents	Biomass	Sewage sludge
Coal	39%	20%	20%	20%	20%	20%	20%
Pet coke	20%	10%	10%	10%	10%	10%	10%
Oil	0%	0%	0%	0%	0%	0%	0%
Natural gas	25%	54%	25%	25%	25%	25%	25%
Scrap tires	3%	3%	33%	3%	3%	3%	3%
MSW	3%	3%	3%	33%	3%	3%	3%
Waste oils & solvents	9%	9%	9%	9%	39%	9%	9%
Biomass	0%	0%	0%	0%	0%	29%	0%
Sewage sludge	0%	0%	0%	0%	0%	0%	29%

Table A5. Resulting fuel mix from 100% replacement scenario

Fuels	Baseline	100% of coal and pet coke replaced with:					
		Natural gas	Scrap tires	MSW	Waste oils & solvents	Biomass	Sewage sludge
Coal	39%	0%	0%	0%	0%	0%	0%
Pet coke	20%	0%	0%	0%	0%	0%	0%
Oil	0%	0%	0%	0%	0%	0%	0%
Natural gas	25%	84%	25%	25%	25%	25%	25%
Scrap tires	3%	3%	62%	3%	3%	3%	3%
MSW	3%	3%	3%	62%	3%	3%	3%
Waste oils & solvents	9%	9%	9%	9%	68%	9%	9%
Biomass	0%	0%	0%	0%	0%	59%	0%
Sewage sludge	0%	0%	0%	0%	0%	0%	59%