Decarbonizing the Cement Industry: Utilizing ReEngineered Feedstock as a Reliable Alternative Fuel

Executive Summary

The global cement industry is a significant contributor to anthropogenic greenhouse gas (GHG) emissions, namely carbon dioxide (CO_2). Among multiple contributing sources throughout the manufacturing process, these emissions primarily result from thermal energy inputs required in the clinker manufacturing process as well as the release of bonded CO_2 during clinker calcination. Multiple bodies of research presented in the following discussion display the advantages of increased alternative fuel (AF) use for lessening these impacts and reducing the industry's contribution to GHG emissions, primarily through the displacement of fossil fuels. While a variety of solid and liquid AFs are currently utilized commercially on a global scale, there are notable environmental and economic benefits that can be realized from the combustion of municipal solid waste (MSW)-derived fuels for the generation of thermal energy. These include the consistent availability of incoming materials already requiring beneficial management, the high biogenic carbon content within waste stream constituents, the ability of the cement plant's combustion zones to destroy organic compounds and other potentially harmful pollutants, the ability to incorporate residual fly ash into the clinker mixture, and ultimately the overall low capital expenses associated with immediate environmental improvements.

Accordant Energy's advanced new fuel derived from the non-recyclable components of such MSW streams offers promising advantages as an AF. Trade-named ReEngineered Feedstock, this customizable product maximizes and builds upon many of the above-mentioned benefits through standardized and homogenous physical and chemical compositions, regulatory advantages as an EPA-defined Non-Hazardous Secondary Material (NHSM), and the optimization of material allocations realized in its production process. The following white paper outlines the established uses of AFs in the cement industry, their recognized potential to cost-effectively assist in significant environmental improvements, and the potential uses and benefits of ReEF in multiple pyroprocessing stages.

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Part I – Cement Emissions and the Case for Alternative Fuels:

Cement-Related GHG Emissions

Cement represents one of the most important building materials in the world. Acting as a primary binding ingredient in a variety of concretes, mortars, stuccos, and more, it is a crucial component of nearly all man-made infrastructure. Accordingly, cement manufacturers comprise a remarkably large global industry and production volumes have increased steadily over recent time. As reported by CEMBUREAU, world production amounted to just under 4.2 billion tons in 2014, increasing by approximately 92% since the year 2004.[1] China ranks as the top cement-producing country in the world, accounting for just under 60% of total production in 2016, and India follows as the second-highest producer at just under 7% for the same year.[2] The US ranks as the third highest at just over 2% of global production, generating 82.9 million tons of Portland cement and 2.5 million tons of masonry cement in 2016, and continuing a positive growth trend over recent years.

The manufacturing process for generating these volumes of material requires significant energy inputs, particularly of thermal energy for clinker calcination, which accounts for around 20-25% of cement production costs[3] (though this number can vary widely). While typical energy expenditures vary based on the type of process used (wet, dry, semi-wet, etc.), they generally span 3.2-6.3 GJ per ton of clinker produced.[4] Given the largely carbon intensive fuel mix used for generation (mainly coal, petroleum, and natural gas[5]), such energy expenditures produce high volumes of GHGs.

Additionally, during the clinker calcination process, carbon bound in raw feed minerals is transformed into bonded CO_2 through carbonate decomposition (generally of limestone) as represented by the below simplified equation:

$$\mathbf{CaCO_3 + Heat \rightarrow CaO + CO_2}$$

The resulting emissions amount to roughly 0.5 kg of CO_2 per kg of clinker produced,[6] notably adding to those generated by fuel combustion.

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[1] CEMBUREAU. *World Statistical Report Edition 2017,* July 10th, 2017, https://cembureau.eu/media/1659/cimeurope_wsr_teaser_2017.pdf.

[2] (Calculated from): United States Geological Survey. "Cement." *Mineral Commodity Summaries 2017,* p. 44, https://minerals.usgs.gov/minerals/pubs/mcs/2017/mcs2017.pdf.

[3] Madlool, N.A., et al. "A critical review on energy use and savings in the cement industries." *Renewable and Sustainable Energy Reviews,* vol. 15, issue 4, 2011, pp. 2042-2060, p. 2043, https://www.sciencedirect.com/science/article/pii/S1364032111000207.

[4] Rahman, Azad, et al. "Assessment of Energy Performance and Emission Control Using Alternative Fuels in Cement Industry through a Process Model." *Energies,* vol. 10, issue 12, December 1 2017, p. 1, http://www.mdpi.com/1996-1073/10/12/1996w.

[5] Rahman, Azad et al. "Recent development on the uses of alternative fuels in cement manufacturing process." *Fuel,* vol. 145, April 1 2015, pp. 84-89, https://www.sciencedirect.com/science/article/pii/S0016236114012381.

[6] Worrell, Ernst, et al. "Carbon Dioxide Emission from the Global Cement Industry." *Annual Review of Energy and the Environment,* vol. 26, 2001, pp. 303-329, p. 316, http://www.annualreviews.org/doi/abs/10.1146/annurev.energy.26.1.303?journalCode=energy.2.

Industry GHG Contribution in Context

Given the high thermal energy inputs required, the nature of the common energy sources used, and the decomposition of carbonates into CO_2 during formation, the clinker production process is evidently a significant contributor to global GHG emissions. While some electrical generation is required for raw material preparation and grinding, these thermal energy and calcination process emissions are generally regarded as the strongest contributors and the main two sources accounted for in measuring cement-related inventories.[7] While fuel requirements for thermal energy generation will vary system-to-system (impacting contribution ratios), a roundabout estimation indicates process emissions to account for roughly two thirds of industry-emitted CO_2 and fuel use to account for one third.[8]

Scaled worldwide, the cement industry accounts for an estimated 5% of global anthropogenic CO2 emissions[9] (though recent literature has calculated this contribution to be as high as 8%, with the industry emitting 1.45 ± 0.20 Gt of CO_2 in 2016 alone[10]). This indicates a sector with notable room for improvement in scaling down GHG contributions while quite effectively taking part in climate change mitigation. And, as displayed in the following, such improvements can provide significant economic upsides through resource risk management and heightened environmental compliance.

Identified Pathways to Scale Down Cement-Related Emissions

Considering the industry's high GHG contributions and their associated climate impacts, identifying methods for decarbonization is critical. And, to date, various technologies and strategies have been developed and utilized. These namely include: the increased adoption of dry-process kilns with pre-heater and pre-calciner technologies; additional energy efficiency improvements; the use of alternative binders as clinker substitutes; the combustion of alternative fuels (AFs).

While these first three options do offer their own benefits and certainly warrant deployment, they also present some drawbacks. As discussed in a study from the Carbon War Room (CWR) examining the potential for gigaton-scale CO_2 reduction in the industry, energy efficiency improvements and pre-heater/pre-calciner upgrades often entail large capital expenses (CapEx), presenting a particular challenge to highly leveraged cement plants with existing high CapEx

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[7] Andrew, Robbie M. "Global CO2 emissions from cement production." *Earth System Science Data* (manuscript under review). August 23 2017. Available at https://www.earth-syst-sci-data-discuss.net/essd-2017-77/essd-2017-77.pdf

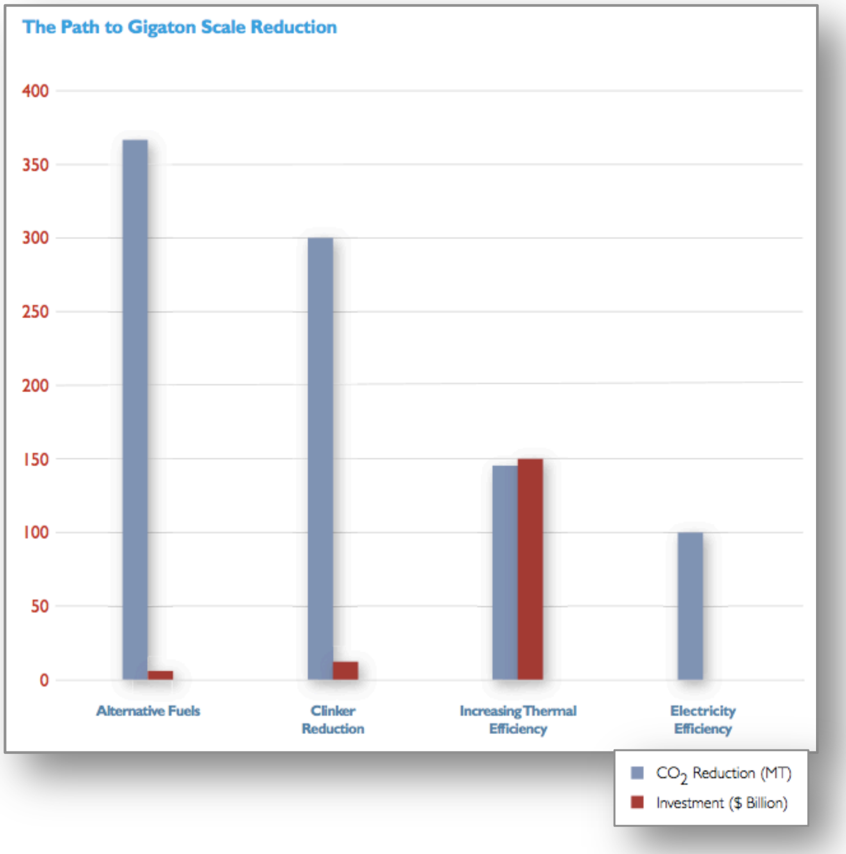
[8] International Energy Agency, World Business Council for Sustainable Development. *Cement Technology Roadmap 2009: Carbon emissions reductions up to 2050,* 2009, p. 4, https://www.iea.org/publications/freepublications/publication/Cement.pdf.

[9] Worrell et al. 2001.

[10] Andrew 2017, p. 1.

requirements.[11] Also as explained by the CWR, the substitution of clinker in alternative/blended cements tends to impact desired physical characteristics of the end-product, rendering it a more niche-specific solution.[12] As such, existing product standards and specifications can act as barriers to their increased application[13] (i.e. the ASTM C618-15 Standard Specification of Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete[14]*).*

Figure 1: *(Used with express written permission from Rocky Mountain Institute/Carbon War Room)*



Accordingly, the combustion of AFs represents a strong carbon mitigation option for the cement industry with high effect and low costs. As quoted in CWR's report, "(t)he largest potential source of reductions with proven technology is the accelerated use of alternative fuel."[15] Figure 1 (right), retrieved from the same page, depicts the CO_2 reduction potential and associated investment costs of these above-mentioned solutions, illustrating the preferability of AF use.

As AFs are often cheaper than conventional fossil fuels, their employment can be an effective method for lowering production costs.[16] Their sourcing can also mitigate risks associated with reliance on non-renewable resources, which is of particular importance to such a fuel-intensive industry.

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[11] Gupta, Arjun. *Gigaton Analysis of the Cement Industry: The Case for Rapid Adoption of Proven Technologies,* Carbon War Room, 2011, https://d231jw5ce53gcq.cloudfront.net/wp-content/uploads/2017/04/CWR_Cement_Report_2011.pdf.

[12] Gupta 2011, p. 4.

[13] Worrell et al. 2001, p. 324.

[14] The ASTM C618-15 standard's terminology (see 'Note 2' in the standard) excludes the use of any MSW incinerator ash or MSW and coal co-combustion residues produced by Electric Generating Units (EGUs) - even those produced from highly processed, non-waste designated fuels - in Class C and F fly ashes. The resulting inability to utilize these co-fired residues in accordance with this standard imposes significant supply issues for cement kilns in need of material as well as cost issues for EGUs due to alternative treatment and disposal requirements.

[15] Gupta 2011, p. 8.

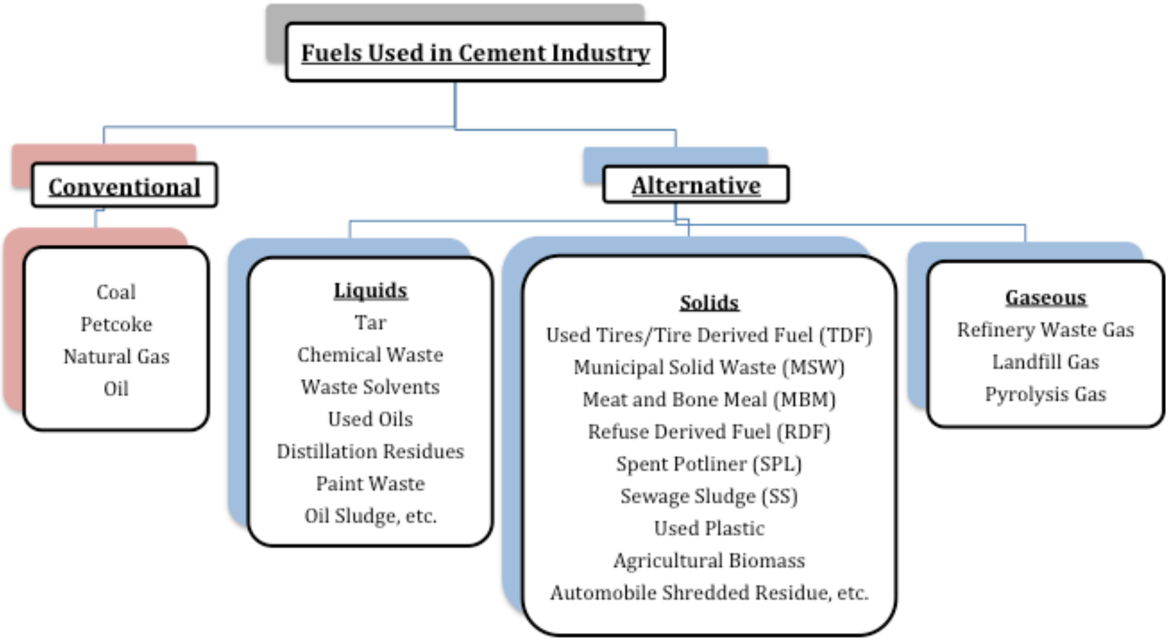
[16] Chinyama, Moses P.M. "Alternative Fuels in Cement Manufacturing." *Alternative Fuel,* edited by Maximino Monzanera, August 9 2011, p. 265. https://www.intechopen.com/books/alternative-fuel/alternative-fuels-in-cement-manufacturing.

Obvious environmental benefits to AF utilization include the direct displacement of fossil fuels, the avoidance of alternative disposal methods, and the ability to incorporate ash residuals into the cement mixture (avoiding the necessity for further treatment and disposal, as discussed more below). And, from a technical standpoint, cement calciners and kilns are well-suited for AF combustion, largely due to their highly alkaline environments and oxidizing atmospheres, high combustion temperatures, and long residence times.[17] While there is potential to fire AFs in up to 100% displacement of existing fuels,[18] they are commonly co-fired with existing fuels.

Established Uses of Alternative Fuels

AFs have been commercially utilized in cement manufacturing for over 30 years.[19] In addition to gained environmental benefits and cement plants' abilities to combust a variety of materials, this is in part due to their economic superiority over fossil fuels, as a majority are sourced from wastes. Figure 2 (below) discerns between many of the conventional and alternative fuels used in the industry and illustrates the large variety of solid, liquid, and gaseous AFs in existence:[19]

Figure 2:



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[17] Chinyama 2011, p. 266.

[18] Gupta 2011, p. 11.

[19] Modified from: Rahman, et al. 2017, p. 5.

Many of these products and others are effectively combusted in cement plants worldwide and in some capacities at high substitution rates (particularly in Europe).[20] Table 1 (below) displays alternative fuel substation rates achieved in various countries and regions as retrieved from a 2015 review published in *Fuel.*[21]

Table 1:

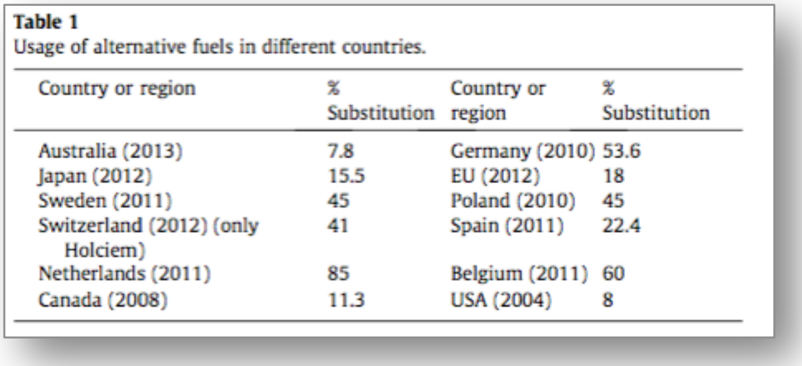

Table 1
Usage of alternative fuels in different countries.

Country or region	% Substitution	Country or region	% Substitution
Australia (2013)	7.8	Germany (2010)	53.6
Japan (2012)	15.5	EU (2012)	18
Sweden (2011)	45	Poland (2010)	45
Switzerland (2012) (only Holciem)	41	Spain (2011)	22.4
Netherlands (2011)	85	Belgium (2011)	60
Canada (2008)	11.3	USA (2004)	8

Figure 3:

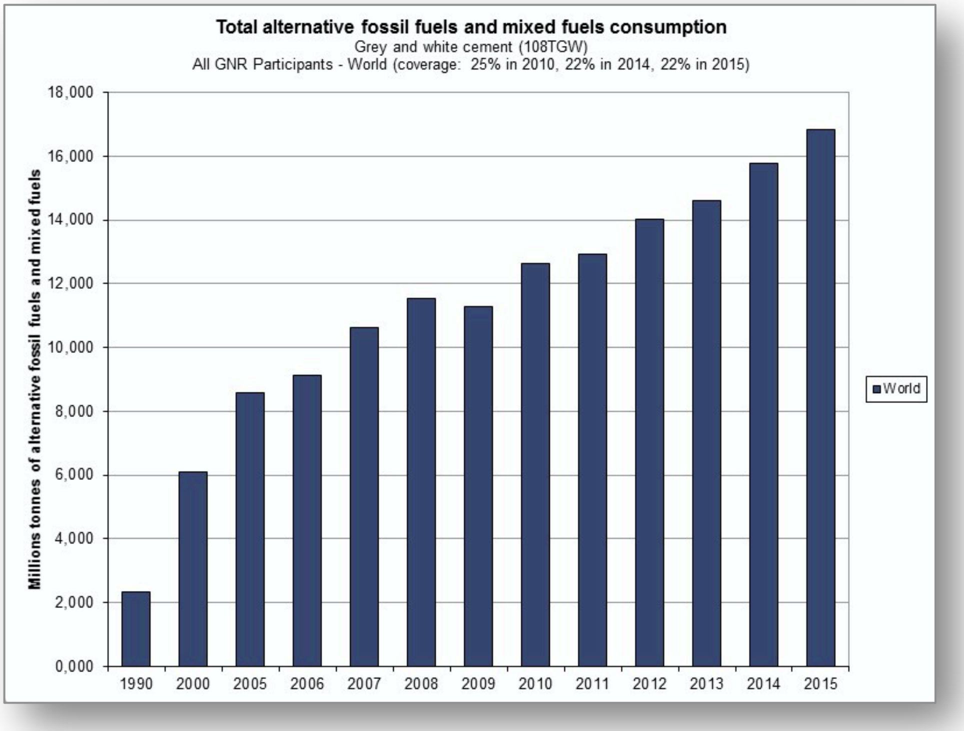

Figure 3 (above) displays total alternative and mixed fuel consumption from 1990 to 2015 as reported in the World Business Council for Sustainable Development Cement Sustainability Initiative (WBCSD)'s Getting the Numbers Right (GNR) database.[22] (The GNR database is an independently managed and third-party verified database containing fully validated production, consumption, and energy

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[20] Rahman, Azad, et al. "Impact of alternative fuels on the cement manufacturing plant performance: an overview." *Procedia Engineering,* vol. 56, 2013, pp. 393-400, p. 396. https://www.sciencedirect.com/science/article/pii/S187770581300492X.

[21] Rahman, et al. 2015, p. 87.

[22] http://www.wbcsdcement.org/GNR-2015/index.html

usage data reported by individual companies and analyzed/summarized by PricewaterhouseCoopers[23].) As displayed, usage of alternative fuels (for GNR participants, accounting for roughly 20-25% of global production and comprised of multiple major cement companies) has increased at a fairly steady rate from year to year. Such increases can largely be attributed increasing pressures from environmental agencies and AFs' benefits in cost-effectively reducing emissions while conserving non-renewable resources.[24] However, as discussed earlier, increased AF adoption remains necessary in order to further decarbonize the industry and almost universally, higher substitution rates can be achieved.

In increasing AF utilization, some fuels offer greater potential and/or availability than others. Within the solid fuel category (see Figure 2), MSW represents one of these sources that can create noteworthy direct and indirect benefits. To start, the MSW stream is significant in volume and continues to grow substantially across the globe. This nearly universally necessitates improved management options in order to lessen landfill disposal rates and their associated environmental burdens. As has been well displayed through life cycle analyses, optimization models, and GHG emission inventories, combustion (especially combustion of select non-recyclable materials[25]) represents a superior management method than landfilling, significantly reducing CO_2 and methane emissions and their associated climate impacts.[26]

Importantly, the biogenic portion of a typical MSW stream is relatively high; estimated by the Energy Information Administration (EIA) to comprise 56% of total US MSW shares in the year 2005.[27] As such, its use as a substitute for conventional fossil fuels not only displaces their consumption (therefore conserving non-renewable resources), but also displaces emissions of carbon sequestered millions of years ago with carbon sequestered during more recent vegetative growth. As this biogenic carbon would still be emitted through waste decomposition in landfills, its use for energy recovery represents an environmentally preferable practice, lessening source-side contributions to the global carbon budget.

Finally, as a materials management benefit over other waste-to-energy (WTE) and EGU co-firing applications, residual fuel ashes from waste-derived AF combustion can be reincorporated into the clinker mixture, allowing the complete

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[23] World Business Council for Sustainable Development, Cement Sustainability Initiative. *Cement Industry Energy and CO_2 Performance: Getting the Numbers Right,* http://www.wbcsdcement.org/pdf/GNR%20dox.pdf.

[24] Rahman, et al. 2015.

[25] "Sustainable Materials Management: Non-Hazardous Materials and Waste Management Hierarchy." U.S. Environmental Protection Agency, https://www.epa.gov/smm/sustainable-materials-management-non-hazardous-materials-and-waste-management-hierarchy.

[26] County of Los Angeles Department of Public Works. *Comparative Greenhouse Gas Emissions Analysis of Alternative Scenarios for Waste Treatment and/or Disposal.* February 2016, http://dpw.lacounty.gov/epd/socalconversion/pdfs/CT_Comparative_GHG_Analysis_Feb_2016_Complete.pdf.

[27] US Energy Information Administration. *Methodology for Allocating Municipal Solid Waste to Biogenic and Non-Biogenic Energy*. May 2007, p. 6, https://www.eia.gov/totalenergy/data/monthly/pdf/historical/msw.pdf.

use of incoming materials and avoiding the necessity for additional stabilization/disposal.[28] Given the earlier-discussed inability for any MSW-derived residues from EGUs to be utilized in concrete in accordance with the ASTM C618-15 standard, this importantly allows for increased applications of alternative/blended cements while furthering the beneficial use MSW constituents.

Part II - Accordant's Competitive Product: ReEngineered Feedstock

As displayed above, MSW and its derivatives offer valuable opportunity as an AF source for cement manufacturing, representing a widely available stream of unused calorific value that continues to increase in volume throughout the world. It has been estimated that by 2025, global waste generation will double from 2010 levels to more than 6 million tons per day[29], potentially reaching 11 million tons per day by 2100.[30] However, not all materials in the waste stream are suitable or ideal for combustion and there are significant limitations to its viability as a fuel source. Furthermore, many such materials are still of value as commodities and can be recovered and redirected to higher uses among value chains.

In regards to cement industry applications, many AFs can present technical challenges that limit their potential for high rates of substitution, largely caused by chemical and physical disparities against traditional fuels.[31] Such challenges are of particular concern in regards to MSW and refuse-derive fuels (RDF), which commonly present heterogeneous compositions and notable differences among types.[32] Therefore, fuel pre-treatment is often necessary to ensure physical and chemical uniformity for optimized combustion.

Accordant Energy's technologies provide a cutting-edge solution to all three of these challenges. The company's Multi Material Processing Platform (MMPP) and Advanced Product Manufacturing (APM) systems enable the maximized recovery of recyclable materials before utilizing select, non-recyclables to generate a precisely refined and fully integrated fuel product, ReEngineered Feedstock (ReEF). ReEF is designed for co-firing alongside existing fuels, mimicking their properties in order to achieve complete combustion and high unit performance while ultimately

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[28] Zhang, Jiao. *Energy, environmental and greenhouse gas effects of using alternative fuels in cement production.* Columbia University Department of Earth and Environmental Engineering, January 20 2013, http://www.seas.columbia.edu/earth/wtert/sofos/Zhang_thesis_.pdf.

[29] Hoornweg, Daniel & Perinaz Bhada-Tata. "What a Waste: A Global Review of Solid Waste Management." *Urban Development Series Knowledge Papers.* Sustainable Development Network, World Bank Urban Development and Local Government Unit, no. 15, March 2012, https://siteresources.worldbank.org/INTURBANDEVELOPMENT/Resources/336387-1334852610766/What_a_Waste2012_Final.pdf.

[30] Hoornweg, Daniel, et al. "Waste production must peak this century." *Nature: Comment*, October 30 2013, http://www.nature.com/polopoly_fs/1.14032!/menu/main/topColumns/topLeftColumn/pdf/502615a.pdf.

[31] International Energy Agency, World Business Council for Sustainable Development 2009, *p.* 10.

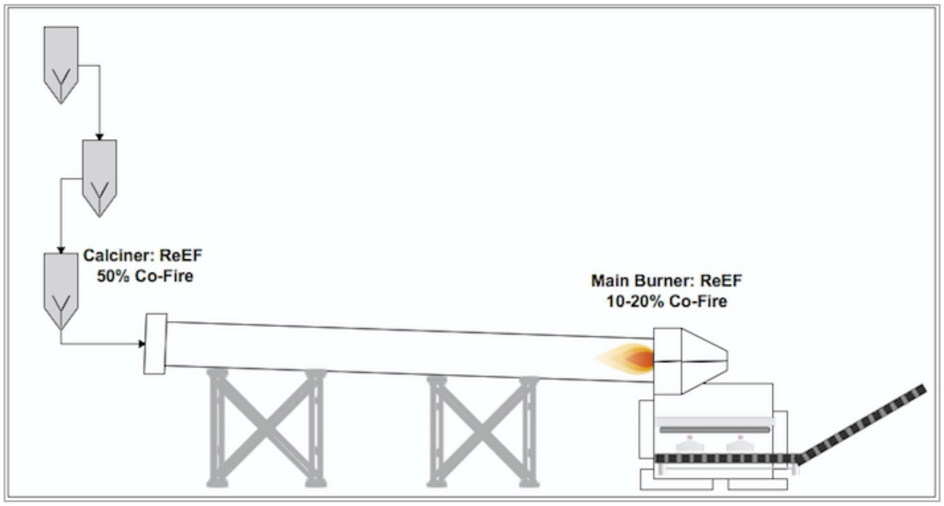
[32] Chatziaras, Nickolaos, et al. "Use of waste derived fuels in cement industry: a review." *Management of Environmental Quality: An International Journal,* vol. 27, issue 2, 2016, pp. 178-193, p. 181, http://www.seas.columbia.edu/earth/wtert/sofos/MEQ-01-2015-0012.pdf.

lowering emissions and providing immediate environmental improvements. The fuel's production process accomplishes necessary pre-treatment to a high degree, rendering a product that matches the specific needs of its' combustion environment as well as the characteristics of the fuels with which it is co-fired. This lends to desired flame profiles in kiln burners and sufficient fuel burnout in calciners, even at reasonably high substitution rates (detailed below). Given such physical and chemical characteristics and consistencies, ReEF is well suited for use in cement production and offers notable advantages as an AF.

Achievable Substitution Rates

The below diagram (Figure 4) displays optimum thermal substitution rates for ReEF in both the calciner and the main burner of a typical cement kiln. As displayed, an approximated 50% yearly average substitution rate can be achieved in the calciner and a 10-20% rate can be achieved in the main burner without negatively affecting production levels, equipment, or clinker quality.

Figure 4:



Higher substitution rates can be achieved in calciners than in main burners, primarily due to their ability to fully combust fuel particles in suspension. In principle, up to a 100% substitution rate can be reached in the calciner, provided a minor to moderate decrease to clinker production rates is acceptable. So, during periods of high demand, a 50% rate is optimal. However, during periods of low demand when plants are running in excess capacity, a higher ReEF substitution rate is achievable and can dramatically reduce variable costs for kiln operators.

In order to maintain a short sintering zone and rapid heat transfer in the kiln (ensuring optimal alite and belite crystal sizes in clinker), as well as to ensure that primary fossil fuels being combusted support the full combustion of relatively coarse ReEF fuel particles (avoiding the possibility for smoldering particles to drop into the clinker load and negatively impact its quality), a lower ReEF thermal substitution rate is expected for the main burner. The above-displayed 10-20% substitution rate would be achieved using a fine fluff form of the fuel (<15 mm).

Pending coal mill capabilities, a pelletized version of the fuel could also be utilized at a higher substitution rate (upwards of 50%).

It should be noted that these are projected possible rates and actual substitution abilities may vary based on kiln characteristics. Additionally, some plant optimization and/or changes to raw meal chemistry may be required when first introducing the fuel in order to maintain desired kiln output and proper clinker chemistry, mineralogy, and granulation. However, as detailed further below, ReEF's consistent quality and availability lend to such changes being minimally necessary and highly cost-effective. And, Accordant possesses the necessary expertise to assist in any pre-use evaluations and potential process adjustments for ReEF customers, further contributing to such a comprehensive fuel solution.

Comparing ReEF to Other Fuels

As mentioned earlier, ReEF's consistent level of homogeneity represents a key benefit over MSW and its other derivatives. Table 2 (below) compares proximate and ultimate analyses of four different MSW samples, illustrating the highly heterogeneous physical and chemical composition of such an unprocessed fuel source. Table 3 (next page) compares ReEF's physical and chemical characteristics against those of bituminous coal, petroleum coke, MSW, and RDF, displaying multiple of the fuel's compositional advantages.

Table 2:

	***MSW A**[33]	**MSW B**[34]	**MSW C**[35]	**MSW D**[36]
Proximate Analysis on Dry Basis (wt %)				
Moisture	33	30.4	29.2	11.7
Ash	13.2	21.9	7.97	44.3
Volatile Matter	45.3	39.3	58.9	44
Fixed Carbon (Calculated)	8.52	8.42	3.99	0.02
Ultimate Analysis On Dry Basis (wt %)				
C	56.3	46.4	49.9	39.3
H	7.15	6.41	7.05	6.81
N	0.3	0.756	0.26	0.23
S	0.09	0.08	0.06	0.05
Cl	1.74	12.32	5.11	1.11
O	14.8	13.6	31	3.32

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[33] Analytical Results submitted to SAIC Energy (see note 35), appendix B, p. 3.

[34] Ibid, p. 4.

[35] Ibid, p. 5.

[36] Ibid, p. 6.

Table 3:

	Coal[37]	**Petcoke**[38]	**MSW A***[39]	**RDF**[40]	**ReEF**[41]
		Proximate Analysis As Received (wt %)			
Moisture	5.53	0.8	33	26.51	3.92
Ash	7.79	0.62	13.2	8.78	8.56
Volatile Matter	35.64	10.4	45.3	61.2	78.36
Fixed Carbon (calculated)	51.04	88.97	8.52	3.5	9.16
		Ultimate Analysis On Dry Basis (wt %)			
C	76.88	89.9	56.3	48.52	57.63
H	4.96	3.93	7.15	6.45	7.95
N	1.66	1.16	0.3	1.2	0.11
S	1.05	6.27	0.09	0.27	0.07
Cl	0.02	N/A	1.74	0.48	0.11
O	7.2	N/A	14.8	31.29	N/A
LHV (Btu/lb)	13510	N/A	6411[42*]	8405	11220
		Ash Analysis (wt %)			
SiO_2	50.09	35.8	N/A	N/A	25.45
Al_2O_3	30.25	29.9	N/A	N/A	18.96
Fe_2O_3	8.92	9.3	N/A	N/A	4.88
CaO	2.08	3.6	N/A	N/A	40.37
MgO	1.07	2	N/A	N/A	1.5
SO_3	1.48	8.5	N/A	N/A	1.89
TiO_2	1.41	0.4	N/A	N/A	3.3
P_2O_5	0.81	1.9	N/A	N/A	0.34
Na_2O	0.4	7.3	N/A	N/A	1.79
K_2O	3.08	1.3	N/A	N/A	1.42

Carbon

As a significant portion of ReEF's carbon content is biogenic (between 56-80% dependent on specific form), geologic (non-biogenic) carbon emissions are directly displaced in proportion to the rates at which the fuel is co-fired (assuming total fuel consumption remains as is). This presents an obvious environmental advantage through the reduction of net fossilized carbon emissions, while also offering a particular cost-saving benefit for kilns that may have compliance

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[37] Analysis Report conducted for South Carolina Electric & Gas Company by SGS North America Inc. August 7, 2017.

[38] C.J. Zygarlicke, J.W. Nowok, D.P.McCollor, K.C. Galbreath, H.A. Kiel, A. Bos and H.J.M. Visser: Coal ash behavior in reducing environments (CABRE) II, Energy & Environmental Research Centre, University of North Dakota (1999).

[39] Analytical Results submitted to SAIC Energy, Environment & Infrastructure, LLC by Interpoll Laboratories, December 7, 2012. Retrieved from Solid Waste Composition Study conducted by Covanta Hennepin ERC pursuant to Title V Air Emissions Permit (05300400-003), December 18, 2012, Appendix B, p. 3.

[40] P. Vounatsos, K. Atsonios, M. Agraniotis, K. Panopoulos, P. Grammelis. Deliverable 4.1: Report on RDF/SRF gasification properties, LIFE09 ENV/GR/000307, Energy-Waste, January 15, 2012.

[41] Analysis Report conducted for Accordant Energy LLC by SGS North America Inc. July 14, 2015.

[42] **Value taken from as-received analysis*

obligations under carbon regulation schemes (i.e. California's AB 32 Cap-and-Trade program[43]).

Nitrogen and Sulfur Oxides

In comparison with exclusive coal combustion, co-firing with ReEF can reduce thermal nitrogen oxide (NOx) concentrations in kiln gas prior to the utilization of selective non-catalytic reduction (SNCR), thereby lowering consumption of ammonia or urea. In cases where no SNCR is used, ReEF can reduce thermal NOx levels in kiln exit gases. This is primarily achieved through the fuel's high volatile content (displayed above at 78.36% by weight), low nitrogen content (displayed above at 0.11% by weight, which also lends to lower fuel NOx production), and its lower peak flame temperatures.

ReEF's low sulfur content in comparison with conventional fossil fuels (displayed above at 0.07 percent by weight) allows for notable decreases in sulfur dioxide (S02) emissions, proportionate to its thermal substitution rate.

Chlorine

A significant challenge to AF use (particularly relevant to MSW-derived AFs) is the potential for high chlorine contents within fuel products, which can lead to excessive salt volatization and enrichment in kilns.[44] This causes unwanted build-up in kiln inlets, risers, calciners, and preheaters and resulting operational problems for kiln systems. As such, ReEF's low chlorine content (displayed in Table 2 at an average 0.11% by weight) represents a critical strong point over MSW and traditional RDFs, achieved during pre-processing through the exclusion of poly-vinyl chlorides (PVC) and other prohibitive contaminants. This allows the fuel to be co-fired without contributing to such unwanted effects as well as mitigates the necessity for excessive chlorine bypass utilization, which can negatively impact kiln efficiencies.

A Total Solution: Consistent, Reliable, and Long-Term Supply

As prefaced earlier, ReEF's high compositional consistency and long-term reliable supply together represent a key benefit of the fuel and its production model. Once ReEF has been tailored to meet a cement plant's specifications and (if required) any modifications have been made to equipment for usage optimization, it can be delivered in a consistently precise and homogenous form for a guaranteed length of time, as determined through plant-specific off-take agreements. This allows for process optimizations to provide longer-enduring benefits, and ultimately

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[43] California's Cap-and-Trade program (established under the AB 32 Global Warming Solutions Act) requires cement plants to obtain and surrender carbon credits in order to account for their GHG emissions. Importantly, the biogenic carbon content of ReEF does not trigger a compliance obligation under this program. As such, the fuel can both lower compliance costs for plants through displacing carbon emissions as well as allow for the sale of any freely allocated allowances in surplus after this lower carbon intensity is accounted for, ultimately creating valuable economic incentive for its adoption.

[44] Zhang 2013, p. 19.

maintains steady kiln operations, consistent clinker quality, and stable emissions levels.

Such customizability and consistency in product critically distinguishes Accordant from fuel brokers (who typically market set volumes of various materials, continuously necessitating plant equipment modifications and changes raw meal chemistry), and enables a more complete fuel solution for plant operators. Through the ReEF production model, Accordant is able to work in direct collaboration with off-take customers in designing a fuel that meets desired criteria and ensures optimal plant performance and end-product quality. This provides both cost-saving opportunity and ease of implementation for users and represents a noteworthy advantage over other AF procurement options.

Regulatory Advantages: NHSM Categorization and CISWI Emission Guidelines

Cement plants in the United States are subject to a variety of laws and regulations at federal, state, and local levels. Among these, industry emission standards under the Clean Air Act present a notable regulatory requirement for kilns, especially those combusting solid wastes (which are subject to more stringent standards than those combusting traditional fuels). However, as explained below, ReEF's extensive processing prior to combustion legally allows for its usage without triggering such strict requirements.

Until recently, cement kilns combusting MSW in the US were exempt from municipal solid waste combustor standards[45] and therefore not categorized as energy recovery devices under the CAA's definition of Commercial and Industrial Solid Waste Incineration Units (CISWI).[46] As such, these facilities were regulated as standard cement kilns and subject to the National Emissions Standards for Hazardous Air Pollutants for the Portland Cement Manufacturing Industry (PC NESHAP) under section 112 of the CAA.

However the EPA's 2013 revised emission guidelines (EG's) for CISWI, which reached a recent compliance deadline on February 8th of 2018,[47] have now effectively removed this exemption and therefore apply to kilns that continue to combust MSW (and any other solid waste as defined under 40 C.F.R. § 241). As displayed in Table 4 (below), which compares the emission limits under both standards, the CISWI EG impose significantly more stringent requirements than the PC NESHAP.

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[45] 40 C.F.R. § 60.32b (m)

[46] 40 C.F.R. § 60.2265

[47] 40 C.F.R. § 60.2535 (b)(1)

Table 4:

Emission Type	**Emission limits under the PC NESHAP for existing non-waste-burning cement kilns**[48]	**Emissions limits under the CISWI EGs for existing waste-burning cement kilns**[49]
Particulate Matter (PM)	0.07 lb/ton clinker	13.5 mg/dscm
Dioxins/Furans (D/F)	0.2 ng/dscm (TEQ)	0.075 ng/dscm (TEQ)
Mercury (Hg)	55 lb/MM tons clinker	0.011 mg/dscm
Total Hydrocarbon (THC)	24 ppmvd	N/A (see carbon monoxide limit)
Hydrogen Chloride (HCl)	3 ppmvd	3 ppmvd
Nitrogen oxides (NO_x)	1.5 lb/tons clinker[50]	630 ppmvd
Sulfur Dioxide (SO_2)	0.4 lb/tons clinker[51]	600 ppmvd
Carbon Monoxide (CO)	N/A	110 (long kilns) / 790 (preheater/precalciner) ppmvd
Lead (Pb)	N/A	0.014 mg/dscm
Cadmium (Cd)	N/A	0.0014 mg/dscm

*(Note: As not all units are equivalent between both standards, not all comparisons are directly commensurable.)

Alternatively, combusting ReEF as an AF allows for the continued use of an MSW-derived fuel without triggering CISWI EG regulations, as the product is considered by the EPA to meet the processing and legitimacy established for Non-Hazardous Secondary Materials, categorizing it as a non-waste fuel.[52] Kiln operators utilizing ReEF are therefore subject to PC NESHAP standards, presenting a significant regulatory advantage.

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[48] 40 CFR § 63.1343 Table 1.

[49] 40 CFR Part 60 Subpart DDDD, Table 8.

[50] 40 CFR 60.62(a)(3), but applicable only if construction, reconstruction, or modification of the kiln commences after June 16, 2008.

[51] 40 CFR 60.62(a)(4), but applicable only if construction, reconstruction, or modification of the kiln commences after June 16, 2008.

[52] The U.S. EPA has determined and documented for Accordant that ReEF qualifies as a non-waste fuel under Non-Hazardous Secondary Material (NHSM) regulations (40 CFR Part 241) when co-fired in coal power plants. However, the logic and analysis used in this letter would also apply to cement kilns designated for coal combustion and is identical to that used in the NHSM rule. This has been displayed in other determination letters for the use of certain fuels in cement plants (see letter from EPA to Entsorga WV LLC on Dec. 9 2013, available at https://yosemite.epa.gov/osw/rcra.nsf/ea6e50dc6214725285256bf00063269d/e676980825d88d5385257c71005b2c64!OpenDocument. ReEF has a significantly higher Btu/lb and lower sulfur, mercury, chlorine, fluorine, nitrogen and lead emissions than the product described in Entsorga's letter).

Improving Sustainability: Conforming To Key Principles of the Cement Sustainability Initiative

ReEF provides additional opportunity for cement producers to actively take part in improving industry sustainability in collaboration with a variety of related stakeholders, as the fuel assists in partial conformance with the membership requirements of the Cement Sustainability Initiative (CSI). The CSI is a voluntary, CEO-led business initiative operating as a member-sponsored program of the World Business Council for Sustainable Development. It is comprised of 24 major cement producers operating in over 100 different countries and accounting for roughly 30% of cement global production, making it one of the largest sector-specific sustainability initiatives in the world.[53]

Participating companies in the initiative sign the *CSI Charter*, pledging to apply a set of actions and commitments (first established in the initiative's 2002 *Agenda for* Action) as part of their contribution to the industry's sustainable development.[54] General topic areas of these requirements include monitoring and systematically reducing emission levels, measuring and reporting on employee health and safety data, assessing environmental and social impacts, and more. A majority of action items are accompanied by separate guidelines or protocols, and many require the reporting of performance/progress data as well as the reception of assurances from third-party practitioners.

As part of a commitment to the "Responsible Use of Fuels and Raw Materials," members must apply the initiative's *Guidelines for Co-Processing Fuels and Raw Materials in Cement Manufacturing.*[55] ReEF and its production process closely adheres to these co-processing guidelines by nature, positioning it as an AF that can be quickly and easily implemented while still conforming with CSI requirements.

Importantly, the fuel matches all of the basic principles for pre-processing as established in section 4.6 of the co-processing guidelines document.[56] Matching criteria includes: meeting chemical and physical quality requirements to ensure protection of the environment, production process, and end-material produced; maintaining stable energy and mineral contents to allow for optimal feed into the kiln; having a physical form that lends to safe handling, storage, and feeding.

Similarly, ReEF's production facilities (using MMPP and APM technologies) meet the core principles for pre-processing facilities as established in the document.[57] Matching criteria includes: being permitted for waste treatment and

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[53] See website: https://www.wbcsdcement.org.

[54] *The Company Charter of the Cement Sustainability Initiative,* https://www.wbcsdcement.org/index.php/about-csi/csi-charter

[55] *Guidelines for Co-Processing Fuels and Raw Materials in Cement Manufacturing.* http://wbcsdpublications.org/project/guidelines-for-co-processing-fuels-and-raw-materials-in-cement-manufacturing-version-2-0/

[56] WBCSD, CSI Guidelines for Co-Processing p. 17.

[57] WBCSD, CSI Guidelines for Co-Processing p. 17.

managed according to necessary quality, health, and safety procedures by a professional team; accepting a traceable incoming waste stream and consistently determining materials' final destinations (to commodity markets or fuel manufacturing); conforming to a waste processing plan that stipulates quality specifications for the processed waste*;* using quality control and testing procedures to ensure that ReEF meets usage-relevant specifications, will not negatively impact end-product quality, and that incoming fuel constituents have been properly screened and compositionally assessed.

Conclusion

As a strong contributor to global anthropogenic GHG emissions, the cement industry is under increasing pressure to identify and implement methods of decarbonization. Among these, the combustion of AFs represents a commercially viable option that can cost-effectively displace fossil fuel consumption (and reduce fuel-associated emissions) while making beneficial use of otherwise wasted materials. Overall, this offers the ability to lessen reliance on non-renewable fuels (often lowering production costs) while greatly improving environmental outcomes and the sustainability of the manufacturing process. Ultimately, increased AF adoption is both warranted and achievable.

Comprising a stream of notable size, MSW represents a widely available resource already requiring better management. Its use as a fuel can significantly reduce fossilized carbon emissions while avoiding landfill disposal. And, when used in cement kilns, the ability to incorporate residual ashes from its combustion into cement mixes represents a key benefit over its other energy conversion applications.

However, there are significant challenges to utilizing MSW as an AF, primarily due to the stream's vast heterogeneity and resulting chemical and physical inconsistencies among its constituents, which can negatively affect plant equipment, clinker quality, and emissions levels. Furthermore, a large amount of materials in the MSW stream are still of value as recyclable commodities and/or are not suitable for combustion.

ReEF and its manufacturing process provide a total solution to these challenges, transforming non-recyclable materials from the waste stream into a precisely engineered and consistently reliable fuel product. As displayed above, this advanced fuel is well suited for combustion in cement calciners and kilns, allowing for decreased emissions with maintained plant performance. And, as the fuel's extensive processing renders it an EPA-designated non-waste fuel, its combustion does not trigger the comparatively stringent emission standards imposed on other waste-combusting facilities. This not only improves overall environmental impacts, but provides significant cost-saving opportunity and regulatory advantages for users. Finally, Accordant's high level of expertise in combustion engineering allows for ReEF customers to receive a properly engineered and high quality product that will consistently meet desired specifications on a long-term basis. For more information on Accordant's advanced technologies and reliable AF solution, visit www.accordantenergy.com.