International Cement review

Breathing life into fuel use

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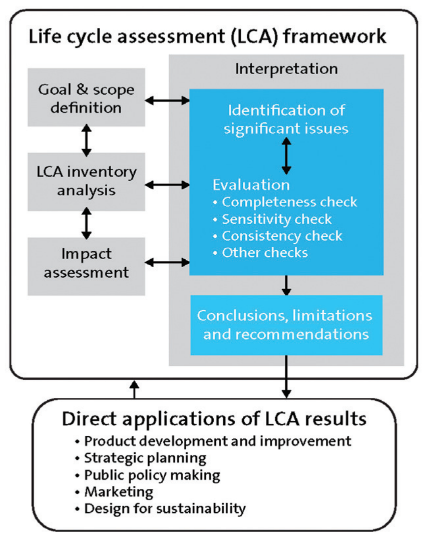
Air Products conducted a Life Cycle Assessment on cement production, which focussed on greenhouse gas emissions (GHG) relating to clinker production. It compared coal combustion using air versus oxygen-enriched air, with the extra oxygen produced via an onsite Vacuum Swing Adsorption (VSA) process or an off-site cryogenic process. The results discussed in this article have been peer-reviewed and have received third-party acceptance in accordance with the ISO standard 14040:2006 for Life Cycle Assessments.

As the second-largest industrial source of CO_2, cement manufacturing produces approximately five per cent of the global anthropogenic CO_2 emissions.[1] The carbon footprint for cement manufacturing has three major sources (see Table 1). Cement manufacturing can reduce CO_2 emissions by switching to raw materials with lower CO_2 emissions, capturing CO_2 and utilising it in a beneficial process, or replacing some fossil fuel (eg coal) with less carbon-intensive fuels or carbon-neutral biomass. Of these three options, the substitution with alternative fuels is fairly common and continues to grow in regions such as Europe, where high waste disposal costs help drive the economics favourably.

While economically attractive, the use of alternative fuels presents a major challenge to the kiln operator. Although there is a wide range of fuels available, their chemical and physical properties vary significantly. Due to the nature of these fuels and their typically lower heating values, there is often a practical limit to substitution levels. Maintaining target temperatures and oxygen levels are paramount to consistent kiln operation and production. If target temperatures cannot be maintained due to the low heating values of the fuels employed, production levels must be curtailed. As a result, overall fuel substitution and the economic and environmental benefits may be limited.

The practical amount of fossil fuel replacement by alternative fuels depends on the characteristics of the fuels, existing combustion system/kiln design and production/quality constraints. The original designs of most existing plants were based on air-based combustion of fossil fuels. As a result, each plant will typically encounter a practical limit to their substitution efforts since alternative fuels generally produce lower flame temperatures, require greater amounts of combustion air, and contain moisture and other components that increase the volume of exhaust gases that must be pulled through the gas circuit. In these cases, oxygen has been shown to enable greater substitution by alleviating the demands on the gas circuit (one volume of oxygen replaces around five volumes of air) and improving combustion efficiency and heat release.



Adapted from EN ISO 14040 & EN ISO 14044

Figure 1: Life Cycle assessment is an iterative process

Using oxygen

Oxygen enrichment improves the combustion of all fuels, increases flame temperature and thereby raises the level of possible alternative fuel substitution. The resulting improved kiln control and stability with oxygen enables operators to maintain feed rates and burn more consistently than with air alone.

The nitrogen component of combustion air is particularly problematic for kilns firing alternative fuels since these fuels generally produce more exhaust gases per thermal input. This is due to their composition and higher moisture content relative to conventional fuels. Excess air requirements increase with alternative fuels, adding even more air, and thus nitrogen, to the system. As substitution levels increase, it is common for the induced-draught fan to reach its operating limit, preventing additional thermal input. Once fan-limited, oxygen enrichment enables increased alternative

Table 1: CO_2 emission sources during (Portland) cement production[2]

CO_2 emission source	*Share (%)*	*Emission type*
Coal combustion to meet large thermal requirement	34	Direct
As by-product of calcining process	54	Direct
Electricity use to drive equipments	12	Indirect

Table 2: matrix of sensitivities and cases considered (x_c refers to the fuel composition)

Cases	*Method 1 (GHG impact of alternative fuel only from difference in x_c and LHV)*	*Method 2 (GHG impact of alternative fuel from incineration to generate electricity)**	*Method 3 (GHG impact of alternative fuel from their carbon neutrality)*
1 Coal + air	×		
2 Coal + alternative fuel + air	×	×	×
3 Coal + alternative fuel + air + off-site ASU O_2	×	×	×
4 Coal + alternative fuel + air + on-site VSA O_2	×	×	×

**25% of thermal energy converted to electricity*

fuel substitution without a further reduction in kiln throughput. Through the use of oxygen, cement plants are able to increase alternative fuel utilisation while maintaining or improving production and quality.

The economics of oxygen-enhanced alternative fuel utilisation are straightforward and easily determined with the fuel prices, oxygen cost and clinker values.[3] In the past, Air Products estimated CO_2 savings based on the fuels being used, but the company recognised that it was not considering all of the potential impact of increasing substitution through oxygen use. Therefore, a Life Cycle Assessment (LCA) approach was undertaken to more rigorously determine the net impact of oxygen-enhanced alternative fuel utilisation on CO_2 emissions. This article takes a detailed look at the methodology and results of the analysis.

What is LCA?

LCA is the comprehensive evaluation of a process in a cradle-to-grave, cradle-to-gate, or gate-to-gate fashion to understand the environmental aspects of a product or a service. The LCA process begins with goal definition, which describes the scope of the study and the assumptions to be made. Next, the inventory analysis is carried out, followed by impact assessment. The results of the process might provide insights that may require changes in the assumptions and the scope. The iterative nature of the process is highlighted in the LCA framework, as shown in Figure 1.

Analysis goal and scope

The goal of this comparative LCA study was to understand the relative greenhouse gas (GHG) emission impact of retrofitting an existing kiln to operate using oxygen-enriched combustion air to increase alternative fuel substitution while maintaining clinker production rates. The functional unit for this study is the production of 1kg of clinker.

The scope of this LCA study was narrowed down to cradle-to-gate type because the alternative fuel substitution does not impact the final clinker product itself (and, hence, its use and disposal). The amount of 'raw meal' required is independent of the fuel-oxidant mixture selected. Hence, the 'raw meal' preparation steps such as quarrying, crushing, blending, storage and preheating are excluded. This translates the cement manufacture system boundaries from feed material entering the kiln line to kiln exit.

For the oxygen and coal used for the clinker production, the scope will include the generation and subsequent use in the kiln. Only waste streams are considered for alternative fuels. Since the alternative fuel is a by-product or waste, its generation is excluded from the analysis. The end-of-life disposal of these waste streams is considered.

In terms of clinker production technologies, only the modern calciner kiln is considered. The scope only includes the scenario for retrofitting an existing kiln since the design of a new unit operation could incorporate modifications to accommodate alternative fuel sources. In terms of alternative fuels used for substitution, the scope is limited to the composition of tyres, waste fuel and waste-derived fuel (WDF), as defined in Table 4. The impact from landfilling this waste (instead of using as secondary fuel) is beyond the scope of this study.

The sources of oxygen supply considered are limited to delivery of off-site generated oxygen via cryogenic air separation and on-site generated oxygen via vacuum swing adsorption (VSA) technology. These are the primary modes for large-quantity oxygen supply to the cement industry today.

Since existing equipment will be used without impacting the capacity, the analysis does not consider the building and demolition of cement plants and the construction and maintenance of transportation systems. The only exceptions are the impacts from construction and installation of VSAs for on-site oxygen, as they would not already exist in non-oxygen-enrichment scenarios.

The transportation impacts for the various fuels and oxygen are considered

Table 3: fuel and oxidant consumption converted to basis of 1kg clinker produced

	Case 1[1]	*Case 2*[2]	*Cases 3/4*[3]
Coal	0.15	0.08	0.06
Tyres	0.00	0.01	0.01
Waste Fuel	0.00	0.01	0.01
WDF	0.00	0.04	0.07
Clinker	1.00	1.00	1.00
Oxygen	0.00	0.00	0.01

[1] *(Coal + Air) data calculated from Case 2 data by replacing Alternative fuels with coal based on their LHV*
[2] *(Coal + Alt Fuel + Air) data from actual clinker operation*
[3] *(Coal + Alt Fuel + Oxygen-enriched Air) data from actual clinker operation*

in terms of distance to be travelled, the amount to be transported and the mode of transportation. Only impacts from the transportation are considered, not from the vehicle production itself.

When considering the oxygen produced off-site at an air separation unit, the inventory assessment is carried out using mass allocation. Mass allocation is an ISO-accepted Life Cycle Inventory methodology in which the environmental 'burdens' of a process are distributed to its multiple products based on their respective mass production rates. No allocation is used in cement manufacturing or coal production. Impacts from avoided incineration of waste are allocated.

Since the focus of this study is to understand the relative impact on GHG from the various fuel-oxidant combinations used to supply the thermal energy needs, the only impact category considered is global warming potential (GWP). GWP impact assessment is carried out using IMPACT 2002+ method included in SimaPro software.

Assumptions

Air Products considered Europe as the region of analysis since cement producers in this region are leading the industry in alternative fuel substitution. The following additional assumptions are made:

- Alternative fuel from sources such as used tyres and spent solvent is transported via a 180-mile round-trip by truck.
- Alternative fuels which are carbon neutral at source, such as biomass, are transported via a 90 mile round-trip by truck.
- Oxygen is produced on-site with VSA generation technology at an oxygen purity of 93 per cent.
- Oxygen is produced off-site via cryogenic distillation in modern air separation units (ASU).
- Oxygen is generated off-site and transported a 180-mile round-trip via trucks from an ASU.
- Emission factors for non-renewable wastes are expressed relative to that of coal based on their lower heating values (LHV) and carbon content.
- Use of waste to provide thermal energy via combustion as a substitute for coal is the best end-of-life option.
- Twenty-five per cent of thermal energy in waste is converted into electricity when the waste is incinerated at a dedicated destruction/incineration facility.
- For oxygen-enriched combustion air and higher alternative fuel utilisation, there will be less electricity consumption due to a reduction of coal to grind and convey, while there will be increased electricity consumption from the conveying/pumping of additional alternative fuels. We assume these impacts are relatively small and will approximately negate each other.

Life Cycle inventory analysis

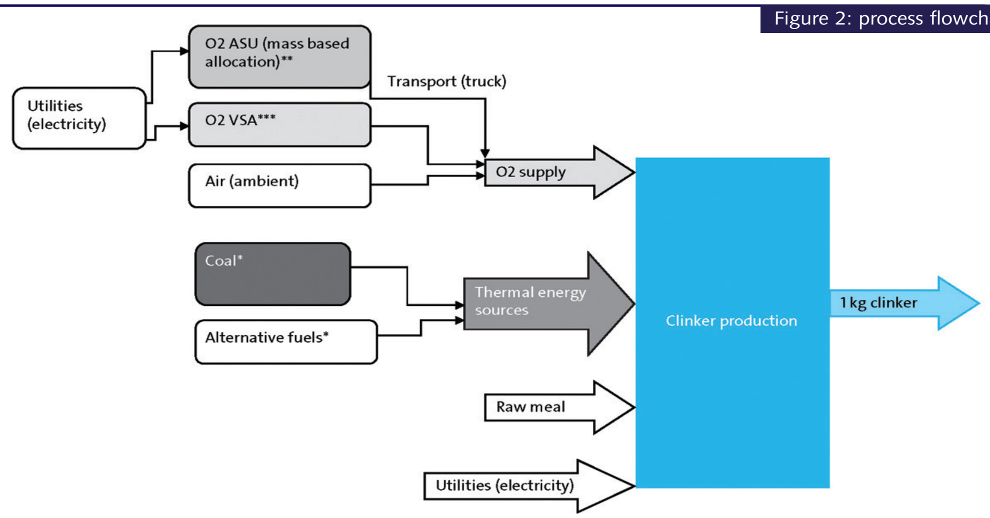
Oxygen enrichment of combustion air will have an impact on GHG emissions related to the thermal energy required for clinker production. This impact is expected primarily from the footprint associated with the production and supply of oxygen, the efficient combustion of the fuel under higher oxygen concentration and the ability to replace greater amounts of fossil fuels (eg coal) with lower-carbon footprint fuels.

The Life Cycle inventory analysis is performed for several scenarios as summarised in Table 2. The resource inputs for the four cases in the table have been presented in Figure 2.

Data used in SimaPro model

This study has been carried out using SimaPro v7.3, a Life Cycle Assessment software developed by PRé Consultants, with certain

Figure 2: process flowchart



**Case 2, Case 3 and Case 4: coal substitution rate with alternative fuels for ambient air combustion and O_2-enrich air combustion depends on the alternative fuel type*
***Case 3: off-site oxygen generation and used only for O_2-enriched air combustion*
****Case 4: on-site oxygen generation and used only for O_2-enriched air combustion*

values such as fuel characteristics entered from literature and fuel efficiency for trucks updated with efficiency for trucks used for liquid oxygen (LOX) transport. The source of CO_2 from fuel combustion is primarily from the oxidation of its carbon content and, hence, maximum CO_2 produced is limited by the carbon content of the fuel, the amount of fuel considered and the efficiency of the conversion of this carbon. In this study, the changes in oxidation source are evaluated as one of the ways to improve this efficiency.

Coal and alternative fuel

Coal sourced in Europe from the Ecoinvent database is used in the model. This model includes the transportation for the coal from the regional storage via four different modes (transoceanic freight, barge, rail freight, and truck). The alternative fuel is the mixture of tyres, waste fuel and WDF in the composition given in Table 3. Emission factors for the non-renewable alternative fuel in relation to coal were estimated using the following equation:

$$\text{Emission factor} = \frac{26.3}{\text{LHV}} \times (1 - \text{Water \& ash content}) \times \frac{\text{Carbon content}}{0.68} \times 2.418$$

where 26.3MJ/kg is the LHV of coal, and 2.418 is kg CO_2 emissions/kg of coal combusted. Based on this equation and fuel characteristics given in Table 3, waste fuel and WDF are identical from GHG emissions perspective and, hence, were treated such in SimaPro. However, it should be noted that the composition of these two alternative fuels will vary in terms of material components impacting other emissions, which are beyond the scope of this study.

Clinker production

Baseline process parameters to produce 1kg of clinker are shown in Table 4. Only the GHG impact from the use of fuel and oxidant are considered since this is a comparative study for identical production rates. Table 4 provides the operational data on the efficiency impact when alternative fuel is used to partially substitute coal (Case 2 and Case 3). These data have been converted from actual data to 1kg clinker production basis.

Waste scenarios

Since the clinker quality and the actual production process is not impacted, there will be no difference in the waste generation and handling from the kiln between the options considered. Therefore, that is not evaluated. However, it must be noted that the alternative fuel used to partially substitute coal is the waste stream from several sources. Hence, the use of alternative fuel in the production of clinker is one of the waste scenarios for this alternative fuel mix. Another waste scenario considered is incineration of this alternative fuel to generate electricity at 25 per cent energy content conversion. This means the alternative fuel taken away from the incinerator generating power towards meeting thermal energy needs for the clinker production will require use of other resources, such as coal, to generate this power.

LCA results and interpretation

LCA results confirm the GHG contribution of the oxygen generation (either from VSA or ASU) to be very small relative to the GHG impacts from coal combustion to provide the needed thermal

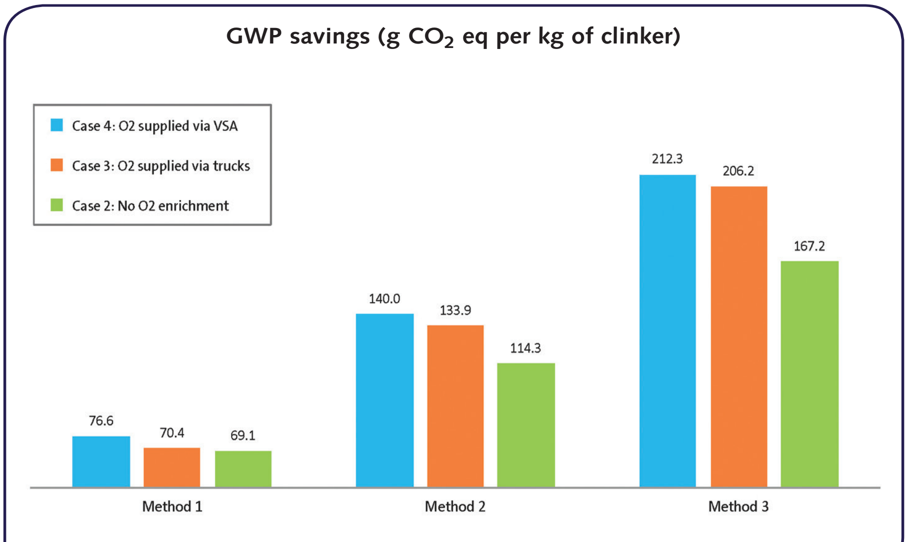


Figure 3: GWP savings from coal substitution with alternative fuels (AF) for 1kg of clinker produced

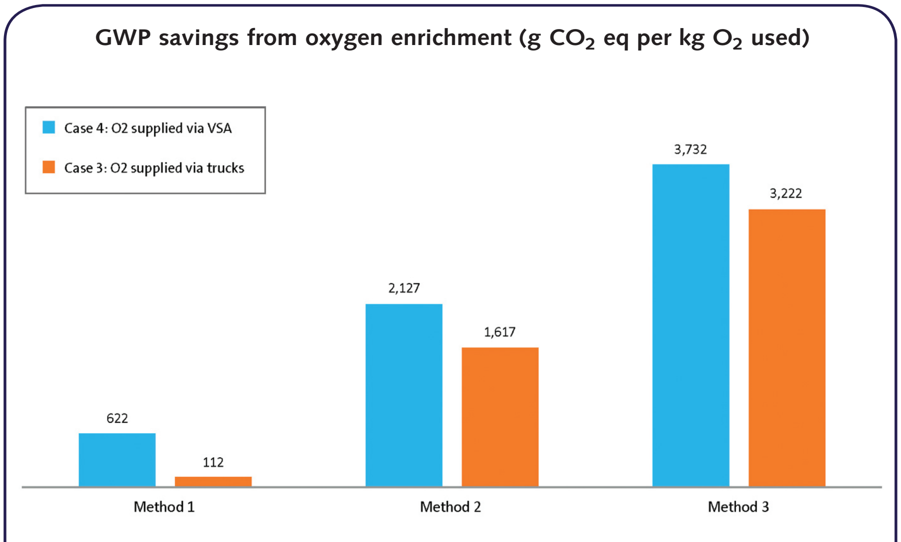


Figure 4: GWP savings from increased coal substitution with AF due to use of 1kg of oxygen

energy. These results also confirm the GWP savings from substitution of the coal with the alternative fuels. The actual savings will depend on the GHG value of these alternative fuels for a given region and which of Method 1, Method 2 and Method 3 more closely reflects the local regulations and conditions. Figure 3 graphically summarises the results and provides a sample GWP savings in g CO_2 eq/kg of clinker produced. These GHG emission savings are significantly high when renewable and/or otherwise incinerated alternative fuels (ie for Method 2 and Method 3) are used. These GWP savings can be further increased through oxygen enrichment by allowing higher alternative fuel usage without sacrificing clinker production capacity. A relatively small amount of oxygen consumption can lead to significant GHG emission reductions, as highlighted in Figure 4.

Sensitivity analysis and uncertainty

Several sensitivity analyses were identified to validate the assumptions made regarding the transportation and production of oxygen, the transportation of the fuels, the fuels' GHG impact and the end-use treatment of the alternative fuels. The sensitivity analysis indicates negligible impacts on the overall results as the assumption values were varied within expected practical ranges.

Conclusion

As this study suggests, coal substitution via alternative fuels for clinker production can yield significant GWP savings. This GWP saving can be further improved through oxygen enrichment, which allows a higher amount of coal to be replaced by alternative fuels. Depending on the methodology and mode of supply, this additional GWP savings can range between 10-27 per cent.

References

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[3] FARMER, L, KISTLER, M AND YANISKO, P (2011) 'Oxygen Economics' in: *ICR*, May, p109-114.

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[5] Ecoinvent report No. 7.

Table 4: characteristics of coal and alternative fuels evaluated in this study[4]

	LHV (MJ/kg)	*Carbon content (by dry weight)*	*Water & ash content*
Coal [1]	26.3	0.68	-
Tyres [2]	32.5	0.56	0.03
Waste fuel	25.0	0.48	0.16
WDF	25.0	0.48	0.16

[1] Another data set [5] suggests: LHV of 29.3MJ/kg with 0.85 C-fraction on dry-weight basis and 3.11kg CO_2 emission/kg coal

[2] Tyre carbon content is back calculated from listed carbon equivalency numbers and compares very well to 0.55 dry-weight fraction from literature.[5]

315-13-005-GLB

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