USE OF SECONDARY FUELS IN THE CEMENT MANUFACTURING: A CASE STUDY

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ABSTRACT

As one of the most energy intensive consumers, the cement industry has long pioneered substitution of fossil fuels by alternative fuels (AFs). Municipal, agricultural, commercial, industrial wastes, biowastes and industrial sludges, animal and wood processing wastes, cutting oils and spent solvents, as well as end-of-life consumer products such as tires and auto shredded residues, are the main sources of AFs. Based on a stoichiometric balance of AF combustion, the present study assesses the use of more than 20 distinct AFs classified according to Eurocodes. The operational efficiency and the emission rates in an actual dry process clinker plant are analyzed. It is shown that the type of AF significantly affects the individual kiln/precalciner/preheater species flowrates and the overall flue gas flow rates. Based on the kiln flue gas rates, overall off-gas flow rates from the main air-pollution control system (APCS), i.e. the kiln/ raw mill APCS, are determined under compound operation, taking lime dissociation, raw mill air and exhaust blower draft into account. Off-gas rates impinge on the mean residence time in the APCS and associated removal efficiency. Non-biogenic carbon dioxide emissions are also affected due to varying renewable constituents in various AFs. Varying off-gas flow rates affect emission rates of conventional and trace hazardous compounds. Emission rates are determined assuming that the plant operates at the compliance limit. The latter is often the case for most actual plants for at least one pollutant; in the present case NOx emissions are assumed to be the limiting pollutant emissions. The limit of these emissions for cement plants using AFs has been restricted by enacted legislation to 500 from the current 800 mg/Nm³, effective on 01.03.2017.

key words: Alternative fuels; cement manufacturing; resource recovery; clinker process.

INTRODUCTION

Cement plants are large industrial facilities located nearby appropriate quarries and easy transportation crossroads (fig. 1) Cement is made from clinker, the product of high temperature sintering of soil materials (raw meal), mainly lime (fig. 2) which is calcined to alkaline oxides. Acting as a paradigm of industrial symbiosis fostering dematerialization, cement plants utilize high volumes of byproducts and wastes from several other industries, both organic and inorganic partly substituting virgin raw materials in the raw meal (by about 10% in the domestic
industry [1]. Substitute inorganic materials include quarry fines, lignite and coal ash, concrete returns, demolition wastes, blast furnace slag, foundry sand, red mud from aluminium production, ore rejects, mineral tailings and residues from steel manufacturing.

Substitute organic materials or water-oil mixtures are used as alternative fuels (AFs). They mainly include waste or biomass derived combustible materials [1-15]: wastepaper, cellulosic agricultural residues, agricultural plastic waste from greenhouse horticultures, wood processing wastes, textile industry wastes, wastes from plastics manufacturing, wood, plastic and paper packaging, end-of-life tires, refuse derived fuel, animal byproduct waste, automotive plastic waste, biological and manufacturing sludges, cutting oil emulsions, cable plastic waste, demolition waste, refinery sludges, spent solvents, waste oils, etc. (some Eurocodes given in Table 1).

Enacted legislation [16 – 19], sets strict limits for AF utilization, expressed as standardized emitted concentrations. Led by the Netherlands (82%), overall thermal substitution by AFs in the EU is at 38.7% [4].

Cement kilns reach high temperatures [3] (clinker exits at about 2000°C) surpassed only by plasma gasification. Kiln residence times exceed 12-15 s at temperatures above 120°C and 5-6 sec at temperatures above 1800°C [1]. As intuitively understood, thermal substitution of fossil fuels modifies the volume and composition of flue gases and final offgases, emitted at the main exhaust chimney, after cleaning in the main air pollution control system (APCS) (fig. 2), namely the kiln-soil mill APCS which cleans the kiln flue gases under direct operation (fig.3), or jointly the kiln and soil mill flue gases under compound operation (fig.3). Other emission points and APCS present in cement plants are primarily de-dusting systems (fig. 3). Such modifications affect emissions and emission rates. In addition, varying oxygen and moisture off gas contents affect the standardization factor (dry, 10% oxygen, STP), via which final emissions (off gas concentrations) are assessed and compared to the standard maximum off gas concentration limit. The emission rates of release to the environment are the primary environmental concern. The present work will endeavor to assess the impact of AF utilization on off gas volumes and emission rates in an actual cement plant producing 1.500.000 tons of clinker per year. Section 1 presents the plant characteristics and the candidate AFs, section 2 describes the assessment method and section 3 presents the results and discussion.

1. The Cement Plant

A 1.500.000 tpa clinker, dry-process cement plant, featuring two parallel kiln / precalaciner / cyclone preheater lines is analyzed. The plant is located in Drepanon, Achaia, Greece (fig. 1). It is currently utilizing fossil fuels (70%, Pet Coke 30% coal) in order to meet the total fuel energy demand of 4.600 TJ/a, resulting in a specific energy consumption of \( \varepsilon = 3.550 \text{ kJ/kg clinker} \). Use of alternative fuels (AFs) for 30% thermal Pet Coke substitution is investigated in this work, leading to a fuel mixture of Pet Coke 40%, Coal 40% and AF 30%.

recovered fuel and refuse derived fuel specifications and EN 15359:2011 «Solid Recovered Fuels- Specifications and Classes»).

The plant operates mostly under compound operation, i.e. the soil mill is active when the kiln is operated. The dominant fraction ($\theta$), fig. 2, of kiln/ precalciner /preheater flue gases pass through the soil mill to heat up the raw meal and subsequently they are jointly cleaned together with the raw mill air in the main APCS. The raw mill air is proportional to the raw meal mass ($\alpha_{sm}$ x raw meal). The rest of the flue gases (fraction 1- $\theta$) pass through the fuel mill in order to create an inert atmosphere. Energy is saved by the two main heat integration couplings, (a) heating up of raw meal by the flue gases in the 4-stage cyclone preheater and (b) heating up of combustion air in the clinker cooler. There are several emission points in the plant (fig. 3), yet the most important one is the kiln-raw mill point in which advanced APCS including SNCR NOx removal and hybrid electrostatic filter / bag filter have been installed.

**The Alternative fuels investigated**

Acting as high temperature long-residence-time alkaline scrubbers, cement kilns have been shown capable of efficient co-processing various waste derived AFs. Several AFs are investigated herein (Table 1) for thermal substitution of pet coke, each one as a separate case.

2. **METHOD**

The method is schematically depicted in fig. 4. Individual combustion flue gas flow rates are determined, given the “as received” ultimate analysis of alternative fuels and fuel feed rates. The flow rate of CO$_2$ from lime dissociation is determined from the clinker production level (1.500.000 tpa). The latter is used to determine the raw meal needed, which in turn is used to determine the raw mill air (fraction of raw meal), which is jointly cleaned with the kiln flue gases in the main APCS (figs 2, 3).

2.1 **Kiln Stoichiometry and Mass Balance**

The operation of the rotary kilns operation at high temperatures (above 1.450 °C) is described by the reactions below.

A. **Fuel combustion stoichiometry**

$$C_x H_y O_z Cl_w S_v N_u + (1+E) (x + \phi + v -0,5 z) O_2 + (1+E) 79/21 (x + \phi + v -0,5 z)N_2 \rightarrow$$

$$x CO_2 + 2\phi H_2O + (x + \phi + v -0,5 z) E O_2 + w HCl + v SO_2 +$$

$$(0,5 u + (1+E) 79/21 (x + \phi + v - 0,5 z)) N_2$$ (1)

where

$$C_x H_y O_z Cl_w S_v N_u$$ is the empirical formula of the fuel and

$$\phi = 1/4 (y - w) \text{ if } y > w$$

$$\phi = 0 \text{ if } y \leq w$$ (2)

$$\phi = 0 \text{ if } y \leq w$$ (3)
Fig. 5a gives the individual combustion species flue gas flow rates, i.e. without including the CO₂ generated by lime dissociation and Table 3 gives the overall (mₖ) combustion flue gas flow rates.

**B. Lime dissociation**

\[
\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2 \quad (4)
\]

The following equations are valid [20]

\[
m_{\text{CO}_2,\text{lime},0} = \eta \times \text{MW}_{\text{CO}_2} \times (m_{\text{clinker}} - \text{fuel ash})_0 \quad (5)
\]

\[
V_{\text{CO}_2,\text{lime},0} = \eta \times 22.400 \times (m_{\text{clinker}} - \text{fuel ash})_0 \quad (6)
\]

Raw meal required = \( \frac{m_{\text{CO}_2,\text{lime}} \times (1 + \eta \times \text{MW}_{\text{CO}_2})}{\eta \times \text{MW}_{\text{CO}_2}} \) \quad (7)

where

\[
\eta = \frac{\zeta}{56} \times (1 - \text{MW}_{\text{CO}_2} \times \frac{\zeta}{56})^{-1} \quad (8)
\]

\[
\zeta = \% \text{w CaO in CaCO}_3 \quad (9)
\]

From the fuel analysis the fuel ash is found to be, fuel ash₀ = 8.660 tn/y (~8.000 tn/y from coal) which is three orders of magnitude less than the clinker production level in equations 5 and 6. Using the parameter values in Table 2, the mass flow rate of CO₂ from lime dissociation in the base line scenario (fossil fuels, subscript 0) is found to be \( V_{\text{CO}_2,\text{lime},0} = 86.743 \text{ kg/h} \) and the volumetric flow rate equal to \( m_{\text{CO}_2,\text{lime},0} = 44,160 \text{ Nm}^3/\text{h} \). The raw meal required is found to be, raw meal₀ = 256.744 kg/h.

### 2.2 Determination of off gas flow rates (main APCS, kiln-soil mill)

Based on mild assumptions, overall off gas flow rates (klin-soil mill), \( V_{k,\text{sm}} \), are given by eq. (11) (see Appendix)

\[
V_{k,\text{sm}} = V_{k,\text{sm},0} + V_{k,\text{sm},0} \left\{ (1 + \psi) \theta V_{fg} \text{MW}_{fg} - (1 + \psi) \theta V_{fg,0} \text{MW}_{fg,0} \right\} / \\
\{ \theta V_{fg,0} \text{MW}_{fg,0} + \theta V_{\text{CO}_2,\text{lime},0} \text{MW}_{\text{CO}_2} + \psi \alpha \eta m_{\text{CO}_2,\text{lime},0} (1 + \eta \text{MW}_{\text{CO}_2}) / \eta \text{MW}_{\text{CO}_2} + \psi \theta (m_{fg,0} + m_{\text{CO}_2,\text{lime},0}) \} \quad (11)
\]

where \( \psi \) = the mass fraction of induced air draft from main exhaust blower with respect to overall kiln flue gases

\( \text{MW} \) = molecular weight

\( V_{fg} \) = flue gas volumetric flow rate.
All variables in eq. (11) are known either from baseline operation data (subscript 0) or from the combustion balance under AF utilization. Use of equation (11) gives the off gas volumes, $V_{k,sm}$. Numerical values are given in Table 3.

To determine actual emission rates we proceed as follows. Denoting by $x_i$ the standardized emission limit for any pollutant, the actual pollutant emission rates are given by:

$$r_i = \frac{x_i}{SF}$$

where $SF$ is the standardization factor,

$$SF = \frac{21 - 10}{21 - \%O_2_{k,sm}} \frac{100}{100 - \%H_2O_{k,sm}} \frac{T_0}{T_i} \frac{P_0}{P}$$

and where the off gas water and oxygen %vol concentrations $\%O_2_{k,sm}$ and $\%H_2O_{k,sm}$ are found from the respective off gas content %vol (taking into account the induced air draft from the exhaust blower, as well as the soil mill air) and from the overall off gas volumetric flowrate, $V_{k,sm}$.

$$V_{k,sm \text{H}_2\text{O}} = \frac{100 \left( V_{\text{H}_2\text{O}fg} + V_{\text{pseudo air moisture}} + V_{\text{soil mill air moisture}} \right)}{V_{k,sm}}$$

$$V_{k,sm \text{O}_2} = \frac{100 \left( V_{\text{O}_2fg} + V_{\text{pseudo air O}_2} + V_{\text{soil mill O}_2} \right)}{V_{k,sm}}$$

The volumetric flowrate of the fluegas water and oxygen, $V_{\text{H}_2\text{O}fg}$ and $V_{\text{O}_2fg}$ respectively, are found from the combustion balance. Air moisture is found from the H$_2$O molar fraction=0.0141 at 65% humidity in air. Temperature and pressure are at normal conditions ($T_0$=T, $P_0$=P).

3. RESULTS AND DISCUSSION

Table 3 and fig. 5 show the combustion flue gas volumetric flow rates, as well as the overall off gas volumetric flow rates under compound operation for baseline case (fossil fuels) and various AF utilization scenarios. It is seen that both the flue gas and the off gas flow rates vary under AF utilization: flue gas flow rates from 176.000 to 234.000 Nm$^3$/h, while off gas volumes vary from 551.000 to 617.000 Nm$^3$/h, a change of about 12% with respect to baseline. As a result of the increased offgas rates through the APCS and the continuous emissions’ monitoring system (CEMS) for most AFs, the residence time decreases, resulting in a lower removal efficiency. Thus the control system must be revamped to meet the new needs, especially if some of the limits are stricter under AF utilization (e.g. NOx, starting 01.03.2017). Assuming that such a necessary action will take place, emitted concentrations will not exceed the standardized limit and thus equations 12-15 will be valid. Consequently, maximum actually emission rates may be determined. For instance, for NOx (fig. 6), several AFs feature lower emission rate than the base line, under a maximum limit of 800 mg/Nm$^3$ and all the more so, under the new anticipated stricter limit of 500 mg/Nm$^3$, (fig. 7) which applies for AF utilization.

The SO$_2$ emission rates (fig. 8) are lower for all AFs, as intuitively expected due to the substitution of pet coke which features a larger S content than the AFs. In contrast, TSP emission rates (fig. 9) are anticipated to be higher,
since the enacted legislation [16] allows higher emitted concentrations under AF utilization (30 mg/Nm³ versus 10 mg/Nm³). The AFs under the Eurocodes 13 05 06/07 (oily waters from oil/water separators) and 19 02 03 / 04 (premixed wastes) feature lower off gas volumes and the lowest emission rates for the pollutants investigated. In regard to greenhouse emissions, the overall CO₂ emissions (fig. 10) rise for most AFs due to higher fuel consumption and higher volumes of combustion-generated CO₂. Nevertheless, the biogenic AF CO₂ has to be subtracted from this total figure in order to determine the net CO₂ contribution and to compare with the baseline greenhouse emissions (CO₂eq) for determination of tradeable CO₂ reduction rights. The overall net CO₂ emissions are reduced up to 16% (figs 10, 11).

It is concluded that (a) all AFs substituting for petcoke lead to lower SO₂ emissions (b) the lower NOx emission limit for AF utilization results in lower NOx emission rates by more than 50% and that (c) AFs resulting in low off gas volumes may bring along significantly lower actual pollutant discharge rates to the environment.

ACKNOWLEDGEMENT
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REFERENCES
[9.] CEN/TC 343/WG 2 N081 Draft 5, Solid Recovered Fuels – Specifications and Classes

6


[17.] Directive 2001/81/EC, on maximum emission limits for atmospheric pollutants

[18.] Directive 2010/75/EU on industrial emissions (integrated pollution prevention and control

[19.] Waste Eurocodes, Decision 2000/532/EC

APPENDIX. Proof of eq. 11

Use of conventional fossil fuels (baseline): 
\[(1+\psi) \theta m_{fg,o} + m_{\text{others},o} = m_{k,sm,o} \quad (A1)\]

Use alternative fuels: 
\[(1+\psi) \theta m_{fg} + m_{\text{others}} = m_{k,sm} \quad (A2)\]

where (fig. 2): 
\[ m_{\text{others}} = m_{\text{soil mill air}} + m_{\text{CO}_2,\text{lime}}.\]

Then
\[ (1+\psi)\theta (m_{fg} - m_{fg,o}) + m_{\text{others}} - m_{\text{others},o} = m_{k,sm} - m_{k,sm,o} \quad (A3) \]

**Assumption 1.** Clinker level is assumed approximately constant (an assumption introducing about 10% deviation for up to 30% thermal substitution of fossil fuels by AFs [20]). Assumption 1 implies that raw meal is nearly constant and therefore the CO₂ from lime dissociation is nearly constant. Since the soil mill air is proportional to raw meal it also remains at about the same level. It follows that:
\[ m_{\text{others}} \approx m_{\text{others},o} \quad (A4) \]

for, 
\[ m_{\text{others}} = m_{\text{soil mill air}} + m_{\text{CO}_2,\text{lime}} \text{ and } m_{\text{soil mill air}} \approx m_{\text{soil mill air},0}, \quad m_{\text{CO}_2,\text{lime}} \approx m_{\text{CO}_2,\text{lime},0}. \]

Then eq. A3 becomes:
\[ (1+\psi)\theta (V_{fg} MW_{fg} - V_{fg,0} MW_{fg,0}) = V_{k,sm} MW_{k,sm} - V_{k,sm,0} MW_{k,sm,0} \quad (A5) \]

which, if MW_{k,sm,0} and MW_{k,sm} were known, could be solved for V_{k,sm}, since V_{fg,0}, V_{fg} MW_{fg}, MW_{fg,0} are known (they were determined from kiln stoichiometry, Table 3) and V_{k,sm,0} is known from baseline operation using fossil fuels (V_{k,sm,0} = 578.000Nm³/h).

The baseline offgas molecular weight, MW_{k,sm,0}, can be determined as follows:

**Offgas molecular weight under fossil fuels**

With \( \nu \) denoting the molar volume (\( \nu = 22.4 \text{ lt under STP} \)), from the offgas mass balance it follows that:
\[ MW_{k,sm,0} = \{ \theta V_{fg,0} MW_{fg,0} + \theta V_{\text{CO}_2,\text{lime},0} MW_{\text{CO}_2} + V_{\text{soil mill air},0} MW_{\text{air}} + V_{\text{pseudo air},0} MW_{\text{air}} \} / V_{k,sm,0} \quad (A6) \]

But
\[ V_{\text{soil mill air},0} = \nu m_{\text{soil mill air},0} / MW_{\text{air}} = \nu \alpha_{\text{sm}} (\text{raw meal}_0) / MW_{\text{air}} \quad (A7) \]

\[ V_{\text{pseudo air},0} = \nu \text{ fraction of kiln fluegas} / MW_{\text{air}} = \nu \theta (\psi m_{fg,0} + \psi m_{\text{CO}_2,\text{lime},0}) / MW_{\text{air}} \quad (A8) \]

where (raw meal₀) = m_{\text{CO}_2,\text{lime},0} (1 + \eta MW_{\text{CO}_2}) / \eta MW_{\text{CO}_2}

Substitution of equations A7 and A8 in eq. A6 gives
\[ MW_{k,sm,0} = \{ \theta V_{fg,0} MW_{fg,0} + \theta V_{\text{CO}_2,\text{lime},0} MW_{\text{CO}_2} + \nu \alpha_{\text{sm}} (\text{raw meal}_0) + \nu \theta (\psi m_{fg,0} + m_{\text{CO}_2,\text{lime},0}) \} / V_{k,sm,0} \quad (A9) \]
From eq. A5 it follows that
\[
V_{k,sm} = \{ (1+\psi)\theta V_{fg} MW_{fg} - (1+\psi)\theta V_{fg,o} MW_{fg,o} + V_{k,sm,o} MW_{k,sm,o} \} / MW_{k,sm} \quad (A10)
\]

But since the molecular weight of kiln flue gases is nearly constant (Table 3), use of assumption 1 implies that \(MW_{k,sm} \approx MW_{k,sm,0}\) and then eq. A10 gives
\[
V_{k,sm} = V_{k,sm,0} + \{ (1+\psi)\theta V_{fg} MW_{fg} - (1+\psi)\theta V_{fg,o} MW_{fg,o} \} / MW_{k,sm,0} \quad (A11)
\]

\[
V_{k,sm} = V_{k,sm,0} + V_{k,sm,0} \{ \theta V_{fg,0} MW_{fg,0} - (1+\psi)\theta V_{fg,0} MW_{fg,0} \} / \\
\{ \theta V_{fg,0} MW_{fg,0} + \theta V_{CO2,limc,0} MW_{CO2} + \alpha_{sm} m_{CO2,limc,0} (1+\eta MW_{CO2}) / \eta MW_{CO2} + \\
\theta \psi (m_{fg,0} + m_{CO2,limc,0}) \} \quad (11)
\]
**Table 1** - Alternative fuels investigated in the Case Study (Decision 2000/532/EC)

<table>
<thead>
<tr>
<th>CODE</th>
<th>DESCRIPTION CODE (EUROPEAN LIST OF WASTE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>02 01 03 Plant tissue waste</td>
</tr>
<tr>
<td>2</td>
<td>02 01 04 waste plastics (except packaging)</td>
</tr>
<tr>
<td>3</td>
<td>03 01 05 sawdust, shavings, cuttings, wood, particle board and veneer other than those mentioned in 03 01 04</td>
</tr>
<tr>
<td>4</td>
<td>04 02 21 wastes from unprocessed textile fibres</td>
</tr>
<tr>
<td>5</td>
<td>04 02 22 wastes from processed textile fibres</td>
</tr>
<tr>
<td>6</td>
<td>12 01 05 plastics particles</td>
</tr>
<tr>
<td>7</td>
<td>13 05 07 * oily water from oil/water separators</td>
</tr>
<tr>
<td>8</td>
<td>13 05 08 * mixtures of wastes from grit chambers and oil/water separators</td>
</tr>
<tr>
<td>9</td>
<td>15 01 01 paper and cardboard packaging</td>
</tr>
<tr>
<td>10</td>
<td>15 01 02 plastic packaging</td>
</tr>
<tr>
<td>11</td>
<td>15 01 03 wooden packaging</td>
</tr>
<tr>
<td>12</td>
<td>16 01 03 end-of-life tyres</td>
</tr>
<tr>
<td>13</td>
<td>16 01 19 plastic</td>
</tr>
<tr>
<td>14</td>
<td>17 02 01 wood</td>
</tr>
<tr>
<td>15</td>
<td>19 08 05 sludges from treatment of urban waste water</td>
</tr>
<tr>
<td>16</td>
<td>19 12 01 paper and cardboard</td>
</tr>
<tr>
<td>17</td>
<td>19 12 04 plastic and rubber</td>
</tr>
<tr>
<td>18</td>
<td>19 12 07 wood other than that mentioned in 19 12 06</td>
</tr>
<tr>
<td>19</td>
<td>19 12 08 textiles</td>
</tr>
<tr>
<td>20</td>
<td>19 12 12 other wastes (including mixtures of materials) from mechanical treatment of wastes other than those mentioned in 19 12 11</td>
</tr>
<tr>
<td>21</td>
<td>19 12 11* other wastes (including mixtures of materials) from mechanical treatment of waste containing dangerous substances</td>
</tr>
<tr>
<td>22</td>
<td>19 02 03 / 19 02 04* premixed waste composed only of wastes marked as hazardous* or not</td>
</tr>
<tr>
<td>23</td>
<td>19 08 11* sludges containing dangerous substances from biological treatment of industrial waste water</td>
</tr>
<tr>
<td>24</td>
<td>19 08 12 sludges from biological treatment of industrial waste water other than those mentioned in 19 08 11</td>
</tr>
<tr>
<td>25</td>
<td>19 12 10 combustible waste (refuse derived fuel)</td>
</tr>
</tbody>
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- Classified as hazardous

**Table 2** - Case Study Plant Data (baseline)

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<th>η</th>
<th>ψ</th>
<th>θ</th>
<th>E</th>
<th>ξ</th>
<th>h</th>
<th>MW&lt;sub&gt;air&lt;/sub&gt;</th>
<th>MW&lt;sub&gt;CO2&lt;/sub&gt;</th>
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<td>0.43</td>
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### Table 3 - Fluegas and Offgas characteristics

<table>
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<tr>
<th>CODE</th>
<th>Combustion fluegas flowrate (without CO\textsubscript{2} (V_{fg}^{\text{bc}}) (Nm\textsuperscript{3}/h))</th>
<th>Offgas flowrate, (V_{ks}^{\text{bc}}) (Nm\textsuperscript{3}/h)</th>
<th>(m_{fg}) (tpa)</th>
<th>Molecular weight, (MW_{fg}) (gr/mole)</th>
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</thead>
<tbody>
<tr>
<td>Baseline, (Subscription)</td>
<td>195 379</td>
<td>578 087</td>
<td>8 802</td>
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<td>1 02 01 03</td>
<td>234.210</td>
<td>617 110</td>
<td>9 064</td>
<td>29.98</td>
</tr>
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<td>2 02 01 04</td>
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<td>591 547</td>
<td>9 267</td>
<td>29.95</td>
</tr>
<tr>
<td>3 03 01 05</td>
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<td>602 212</td>
<td>9 226</td>
<td>29.97</td>
</tr>
<tr>
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<td>212.472</td>
<td>593 674</td>
<td>8 900</td>
<td>29.99</td>
</tr>
<tr>
<td>5 04 02 22</td>
<td>212.472</td>
<td>593 674</td>
<td>8 900</td>
<td>29.99</td>
</tr>
<tr>
<td>6 12 01 05</td>
<td>190.445</td>
<td>571 156</td>
<td>9 297</td>
<td>29.94</td>
</tr>
<tr>
<td>7 13 05 07 *</td>
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<td>558 615</td>
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<td>29.99</td>
</tr>
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<td>8 13 05 08 *</td>
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<td>558 615</td>
<td>8 816</td>
<td>29.99</td>
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<tr>
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Fig. 1. Cement plant investigated

Soil Mill → Cyclone → Preheater, Precalculator, Rotary Kiln → Gypsum → Clinker Production

Cement Production/ Packaging → Air Pollution Control Systems → Cleaned flue gas (off gas)

Fuel Mill APCS

Coal and Petcoke Mill → Fuel Mill APCS

Soil Mill

Air, Fuel, Soil materials → Cyclone Preheater, Precalculator, Rotary Kiln → Water Quencher → Rotary Kiln/ Calciner/ Preheater and Soil Mill APCS

Flue gas flow → Compound operation → Direct operation

Fig. 2. Cement plant flow diagram
**Fig. 3.** Case study: Cement plant emission points and offgas flows. Main emission point is the kiln – soil mill APCS (2 stacks with a total of 578000 Nm$^3$/h offgas flowrate)

**Fig. 4.** Schematic description of the method used to assess AF utilization and emissions.
Fig. 5a. Kiln flue gas species’ flowrates under AF utilization (30% thermal petcoke substitution).

Fig. 5b. Flue gas ($V_{fg}$) and offgas ($V_{ksm}$) under AF utilization (30% thermal petcoke substitution).
Fig. 6. NOx emissions based on maximum emission limit (800 mg/m$^3$, dry, 10% v.v. O$_2$) under conventional fuel or AF utilization (30% thermal petcoke substitution)

Fig. 7. NOx emissions based on maximum emission limit (800 mg/m$^3$ under conventional fuel, 500 mg/m$^3$, dry, 10% v.v. O$_2$ under AF utilization) (AF: 30% thermal petcoke substitution)
**Fig. 8.** SO₂ emissions based on maximum emission limit (60 mg/m³ under conventional fuel, 50 mg/m³ under AF utilization, dry, 10% v.v. O₂) (AF: 30% thermal petcoke substitution)

**Fig. 9.** TSP emissions based on maximum emission limit (10 mg/m³ under conventional fuel, 30 mg/m³ under AF utilization, dry, 10% v.v. O₂) (AF: 30% thermal petcoke substitution)
Fig. 10. CO\textsubscript{2} emissions under AF utilization (30% thermal petcoke substitution)

![CO\textsubscript{2} emissions graph]

Fig. 11. Total (with lime dissociation) and non biogenic CO\textsubscript{2} emissions rate under AF utilization (30% thermal petcoke substitution)

![CO\textsubscript{2} emissions rate graph]