LIFE CYCLE ASSESSMENT OF THE USE OF ALTERNATIVE FUELS IN CEMENT KILNS: A CASE STUDY

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ABSTRACT

The benefits of using alternative fuels (AFs) in the cement industry include reduction of the use of non-renewable fossil fuels and lower emissions of greenhouse gases, since fossil fuels are replaced with materials that would otherwise have to be incinerated with corresponding emissions and final residues. Furthermore, the use of alternative fuels maximizes the recovery of energy. Seven different scenaria were developed for the production of 1 ton of clinker in a rotary cement kiln. Each of these scenaria includes the use of alternative fuels such as RDF (Refuse derived fuel), TDF (Tire derived fuel) and BS (Biological sludge) or a mixture of them, in partial replacement of conventional fuels such as coal and pet coke. The purpose of this study is to evaluate the environmental impacts of the use of alternative fuels in relation to conventional fuels in the kiln operation. The Life Cycle Assessment (LCA) methodology is used to quantify the potential environmental impacts in each scenario. The interpretation of the results provides the conclusion that the most environmentally friendly prospect is the scenario based on RDF while the less preferable scenario is the scenario based on BS.

KEYWORDS: alternative fuels; life cycle assessment; cement production; clinker process

INTRODUCTION

Cement is an essential ingredient which fulfills basic needs such as the construction of housing and infrastructure indispensible to mankind and plays a vital part in the global construction industry. The production of cement is accompanied by high energy consumption, requires large quantities of resources and causes significant environmental impacts. It is responsible for nearly 5% of the global CO_2 emissions and substantial emissions of SO_2, NO_X and other pollutants [1-3]. Therefore cement production as an energy intensive process results in significant greenhouse gas (GHG) emissions. The reduction of emissions in this sector may lead to a significant decrease in the overall GHG releases [4].

The cement industry consumes a significant amount of natural resources (raw materials), energy (heat and electricity) and fossil fuel sources (e.g. coal, petroleum coke). This means that the production of cement consumes an important quantity of non-renewable raw materials, which are the basic constituents of the product, as well as fossil fuels which are required in the heating processes. Moreover cement production is responsible for 5% of the global anthropogenic CO_2 emissions and 7% of industrial fuels use [5,6].

Cement consists of a material called clinker which is formed when the raw material limestone is burned at high temperatures in a cement kiln [1]. In this process (called calcination) calcium carbonate decomposes and CO and CO_2 are produced [6]. Calcination is highly important from a climate perspective, since carbon bound in minerals is transformed to CO_2 [7]. Furthermore it typically causes about 50% of the total CO_2 emissions stemming from cement production. A large portion of the remaining emissions originates from combustion of the fuels in the kiln [8,9]. The clinker then is ground to a fine powder and blended with some additives. According to the calcination reaction the production of one ton of clinker requires an average of 1,5 – 1,6 tons of raw materials and most of the material is emitted from the process as CO_2 emissions into the air [10]. Consequently during the heating process in the kiln, CO_2 emissions are generated through the chemical reaction of the materials and by burning the fossil fuels necessary to heat the kiln. The emissions of CO_2 depend mainly on both the type of process and the fuel used [11]. For instance, in a typical dry process with five stage preheater, precalciner and 100% use of petroleum coke as a fuel, CO_2 emissions derived from the chemical reactions are around 0.53 tons of CO_2 per ton of clinker, while CO_2 emissions derived from the fuel consumption are about 0.31 tons of clinker [12-14]. In addition to CO_2, atmospheric emissions from cement plants include other pollutants such as particles, nitrogen oxides (NOx), sulfur dioxide (SO_2), and some minor pollutants [15]. Other environmental issues associated with cement include the energy required for production and transportation of raw materials, fuels, clinker and cement and the impact of mining, resource depletion and waste generation [11, 15]. The emission quantities also depend on the temperature level and the oxygen content during the combustion stages. In addition, kiln emissions can be influenced by flame shape and temperature, combustion chamber geometry, the reactivity of the fuel, the presence of moisture, the available reaction time and the burner design [10].

Traditionally coal has been the basic fuel for clinker production. Nevertheless, a wide range of other fuels are also used, including petroleum coke (petcoke), natural gas and oil. The use of alternative fuels (AFs) in calciner lines began in the mid-1980s and was very quickly incorporated in the precalciner stage [16]. In 2004 in Europe, 6.1 million ton of different types of wastes were used as fuels in cement kilns and one million tons of these wastes were hazardous [12]. Waste fuels with adequate calorific values can replace fossil fuels and allow fossil fuel savings. However, kilns have to be suitable for burning wastes and conditions have to be optimized in order to be able to secure a high energy efficiency [12].

The clinker-burning process offers good conditions for using different types of waste materials, replacing parts of conventional fuels. The typical types of waste fuels (hazardous and non-hazardous) include wood, paper and cardboard, textiles, plastics, processed fractions (e.g. RDF), rubber and tyres, industrial sludge, municipal sewage sludge, animal meal and fats, coal and carbon waste, agricultural waste, solid waste (impregnated sawdust), solvents and related waste and oil and oily waste [18].

According to the European cement industry the substitution of conventional fossil fuels with alternative fuels based on waste can make an important contribution to sustainable development, through the reduction of the global burden of greenhouse gases such as CO_2 emissions. Taking into consideration that during the cement processes a total of 0.83 tons of CO_2 per ton of product (80% of the finished product is clinker) are emitted and the fact that this amount is derived from decarbonation (0.45 ton/ton product), combustion of coal (0.28 ton/ton product) and electricity production in coal fired power plants (0.1 ton/ton product), the use of alternative fuels for cement clinker production is certainly of high importance and an attractive alternative, comparative to non-renewable fossil fuels. Thus, one of the main strategies through which the cement industry may contribute to a reduction in CO_2 emissions is to substitute fossil fuels used in cement kilns with fuels derived from waste [17]. Furthermore according to Best Available Techniques (BAT), a Reference Document for the Production of Cement [12], the main emissions from the production of cement are emissions to air from the kiln system which derive from the chemical reactions involving the raw materials and the combustion of fuels. The main constituents of the exit gases from a cement kiln are nitrogen from the combustion air, CO_2 from calcination of $CaCO_3$ and combustion of fuel, water vapor from the combustion process and from the raw materials and excess oxygen. The utilisation of waste in the cement industry, principally as alternative fuels, is compatible with the general principles of waste management and the principles of sustainable development set by the European Union and with existing EU policies on energy efficiency, climate change and waste management [18]. Also it will help in achieving the targets set in Agenda 21 of the Earth Summit in Rio de Janeiro (1992), the Johannesburg Declaration on Sustainable Development (2002) and the Millennium Development Goals.

The re-use of waste as alternative fuels can make a waste re-usable or recoverable. Therefore, replacement of some conventional fossil fuels with alternative fuels brings both ecological and economic benefits [19]. The benefits of using alternative fuels in the cement industry include reduction of the use of non-renewable, conventional fossil fuels, such as coal and petcoke, as well as the environmental impacts associated with coal mining. In addition the use of alternative fuels maximizes the recovery of energy, contributes towards a decrease of emissions such as greenhouse gases by replacing the use of fossil fuels with materials that would otherwise have to be incinerated with corresponding emissions and final residues. Furthermore the use of alternative fuels maximizes the recovery of the non-combustible part of the alternative fuel material and eliminates the need for disposal of slag or ash, as the inorganic part of them substitutes raw material in the cement [20, 21].

The term Alternative Fuels (AFs) refers to waste materials used for co-processing. Such waste typically includes plastics and paper/card from commercial and industrial activities, waste tires, waste oils, biomass waste, waste textiles, residues from dismantling operations, hazardous industrial waste (e.g. certain industrial sludges, impregnated sawdust, spent solvents). Because some materials have both useful mineral content and recoverable calorific value, the distinction between alternative fuels and raw materials is not always clear. For example, sewage sludge has a low but significant calorific value, and the ash from its combustion contains useful minerals for the clinker matrix [9].

According to the process of clinker production, the use of alternative constituents which help to control the setting time of the cement or have cementitious properties in their own right (blast furnace slag) or affect the consistency of the cement mortar, is extremely important in reducing the environmental impact. This means that they can reduce the quantity of energy-intensive clinker required for each ton of cement and cause further reduction of CO_2 emissions per ton. Consequently, alternative fuels must be used in quantities and proportions with other raw materials in order to achieve the desired balance of material composition in the kiln product and their use has to follow certain basic rules that assure both reduction of the emissions and a decrease of impacts from the operation of cement kiln [22]. These rules include feeding alternative fuels into the most suitable zones of the kiln, feeding materials that contain a lot of volatile matter into the high temperature zone only andavoiding materials that contain pollutants, such as mercury because kilns cannot retain them and frequently monitor emissions [12].

Life Cycle Assessment (LCA) is a suitable tool for the sustainability assessment giving the quantitative and overall information on resource consumption and environmental emissions of the systems investigated [23, 24]. LCA is standardized under ISO 14040, 14041, 14042, 14043, 14044 [25-29]. LCA is a tool for the analysis of the environmental burdens of products or services at all stages of production, consumption, and end use (from "cradle to grave"). Environmental burden includes all types of impacts on the environment including depletion of natural resources, energy consumption, and emissions to land, water and air. The use of LCA ensures that all environmental impacts are assessed within a consistent framework. As such, the possibility of "problem shifting" is minimized [30, 31]. LCA, according to the ISO standards, is carried out in four steps: the goal and scope definition, the inventory analysis, the life cycle impact assessment and the interpretation.

LCA is a suitable tool for assessing environmental impacts of clinker production and its associated supply chains and it has been applied to studies on clinker and cement production, in order to analyze direct impacts from the production site as well as indirect impacts from resources mining and electricity production [10, 32-33].

PURPOSE

In this paper a comprehensive methodology of Life Cycle Assessment (LCA) has been used for the quantification and evaluation of the environmental impacts from the substitution of conventional fossil fuels, coal and petroleum coke (petcoke) by alternative fuels (AFs) such as RDF (Refuse Derived Fuel), TDF (Tire Derived Fuel) and BS (Biological Sludge) in clinker process. The study is restricted to the production of clinker , since it is the dominant process for the creation of environmental impacts in the cement industry. The purpose of this study is to evaluate the environmental impacts of the use of alternative fuels in relation to conventional fuels in a dry process kiln operation.

In this paper a substitution of conventional fuels by different alternative fuels limited to 10% of the required net calorific value (NCV) of conventional fuels for the thermal needs of kiln operation is considered. In addition, a 30% substitution of conventional fossil fuels by alternative fuels is examined. This manuscript presents a cradle-to-grave life-cycle assessment of seven integrated different scenaria.

METHODS

Goal and scope definition

The goal of this study is to evaluate the environmental impacts of the use of alternative fuels (AFs) for clinker production in the cement industry, as well as to explore the benefits of the use of alternative fuels in cement kilns. Moreover, the study focuses on the selection of the most environmentally friendly fuel mixture using conventional fossil fuels (coal or/and petcoke) and different blends of alternative fuels (AFs) such as RDF (Refuse Derived Fuel), TDF (Tire Derived Fuel) and BS (Biological Sludge) or a mixture of them for the clinker production.

In order to identify the best environmental option, seven integrated scenaria for the production of 1ton of clinker in a rotary cement kiln were developed and compared. Each of these scenaria includes the use of alternative fuels such as RDF, TDF and BS or a mixture thereof, in partial replacement of conventional fossil fuels. A spreadsheet model was constructed in order to design the seven integrated scenaria considering the quality characteristics, the stoichiometry and the required net calorific value of the fuels for the production of 1 ton clinker. The spreadsheet model has the capability to estimate the quantity of the raw materials, the energy balance and the emissions in each case. The Life Cycle Impact Assessment methodology was used in order to assess and evaluate the environmental impacts. Regarding the actual application of LCA, SimaPro 7.1 was used to evaluate the environmental impacts of inventory aspects for seven scenaria [34].

Functional unit

According to the recommendations by Boesch et al. [32], Feiz et al. [35] and García-Gusano et al. [36] 1 ton of clinker produced was selected as the functional unit. Thus during the LCA we considered the production of 1 ton of clinker and all results are based on this.

Boundaries of the system under study

The system is defined as an integrated system for the production of 1 ton of clinker in a rotary cement kiln. The system boundary is shown in Figure 1. It includes all the inputs and outputs associated with producing clinker, from raw material extraction to production. It also includes the required fuels and energy for the production of clinker.

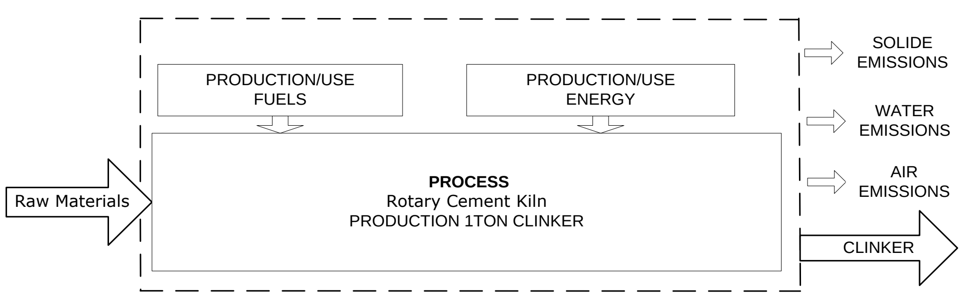

FIGURE 1 - Schematic Flowchart of System Boundary Analysis.

The boundary also includes fuels, energy and emissions associated with the transportation of raw materials from their source to the cement plant. The production of clinker is assumed to take place in a rotary dry process kiln.

Alternative scenaria of clinker production

Seven basic alternative scenaria (Figure 2) of clinker production were investigated in this study. The design of each scenario depends on the use of conventional fossil fuels and alternative fuels (RDF, TDF and BS) which are used to fulfill the total thermal requirements of the production of clinker. According to the design in alternative scenaria 1, 4, 5, 6 and 7 the proportion of coal was considered constant amounting to 30% of the thermal requirements of the clinker production process. The alternative fuels replace 10% of the total calorific value needed for the function of the kiln in scenaria 4, 5, 6 and 7. The description of each scenario is as follows:

- Scenario 1: The thermal requirements for the production of 1 ton clinker are fulfilled by using 30% coal and 70% petcoke. According to the thermal requirements of the process, associated with calorific value of the fuels, it is estimated that the required quantity of coal and petcoke amounts to about 0.0356 ton and 0.0754 ton respectively.
- Scenario 2: The thermal requirements for the production of 1 ton clinker are fulfilled by using 100% coal. According to the thermal requirements of the process, associated with calorific value of coal, it is estimated that the required quantity of the coal amounts to about 0.1186 ton.
- Scenario 3: The thermal requirements for the production of 1 ton clinker are fulfilled by using 100% petcoke. According to the thermal requirements of the process, associated with calorific value of petcoke, it is estimated that the required quantity of the petcoke is to about 0.1078 ton.
- Scenario 4: The thermal requirements for the production of 1 ton clinker are fulfilled by using 30% coal, 60% petcoke and 10% TDF (Tire Derived Fuel). According to the thermal requirements, associated with calorific value of the fuels, it is estimated that the required quantity of coal, petcoke and TDF is about 0.0356ton, 0.0431 ton and 0,0333 ton respectively.
- Scenario 5: The thermal requirements for the production of 1 ton clinker are fulfilled by using 30% coal. 60% petcoke and 10% BS (Biological Sludge). According to the thermal requirements, associated with calorific value of the fuels, it is estimated that the required quantity of coal, petcoke and BS is about 0.0356 ton, 0.0431ton and 0.0667 ton respectively.
- Scenario 6: The thermal requirements for the production of 1 ton clinker are fulfilled by using 30% coal, 60% petcoke and 10% RDF (Refuse Derived Fuel). According to the thermal requirements, associated with calorific value of the fuels, it is estimated that for the production quantity of coal, petcoke and RDF is about 0.0356 ton, 0.0431 ton and 0.0410 ton respectively.
- Scenario 7: The thermal requirements for the production of 1 ton clinker are fulfilled by using 30% of coal, 60% of petcoke and a 10% blend of alternative fuels (Figure 3). This blend consists of alternative flues such as TDF, BS and RDF at 3.33% each. According to the requirements of calorific value it is estimated

that the required quantity of fossil fuels, coal and petcoke, is about 0.0356 ton and 0.0431 ton respectively and the required quantity of the blend of alternative fuels is about 0.0111 ton of TDS, 0.0222 ton of BS and 0.0137 ton of RDF.

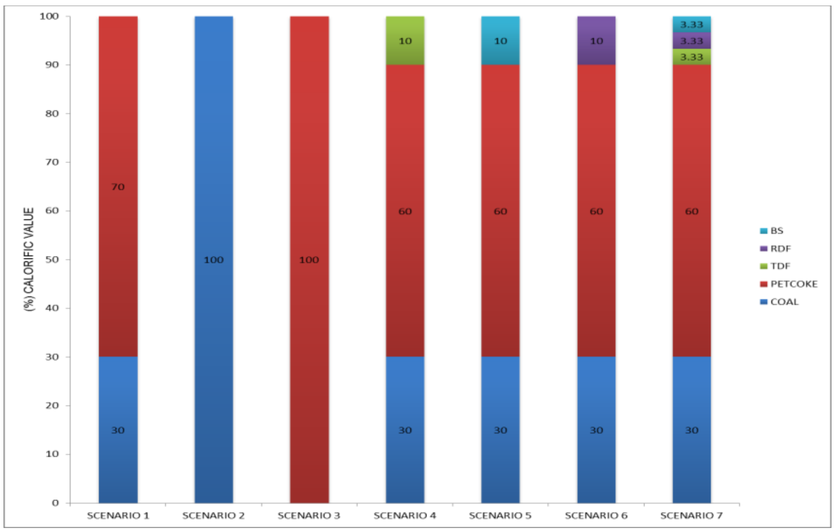

FIGURE 2- Percentage of conventional fossil fuels (coal and petcoke) and alternative fuels (RDF, TDF and BS) per scenario

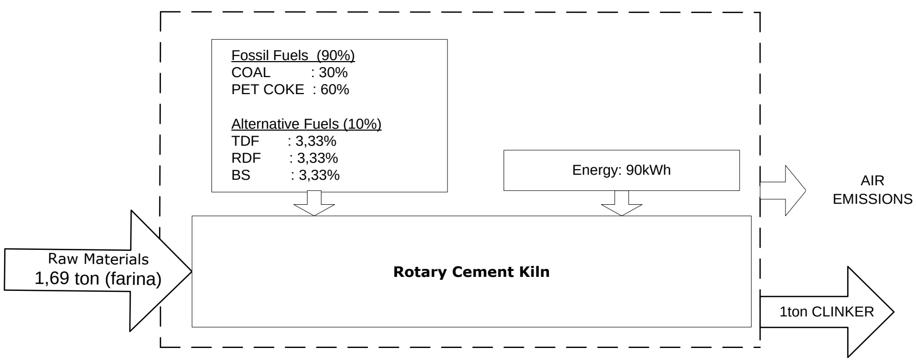

FIGURE 3 - Flow Chart of Alternative Scenario 7

Assumptions

As the integrated system is complex, several assumptions are required for a proper comparison between the alternative scenaria. All considered alternative scenaria should meet the current nationally (Greek) posed legislation limits regarding air emissions and waste handling [12]. Thus, the emissions of CO_2 are estimated to be 900 to 1000 kg/ton clinker, related to a specific heat demand of approximately 3,500 to 5,000 MJ/ton clinker. The CO_2 emissions resulting from the combustion of the carbon content of the fuel are directly proportional to the specific heat demand and the ratio of the carbon content to the calorific value of the fuel [12]. Consequently, the selection of alternative fuels was based on the adequate (net) calorific values. For the combustion process, the chemical and physical quality of the alternative fuels, any specifications or standards ensuring environmental protection, protection of the kiln process and the quality of the product have been taken into consideration. The thermal (fuels) demand for the kiln system and the kiln size is determined by the energy required for the chemical reactions of the clinker burning process (it is about 1,700 to 1,800 MJ/ton clinker).

The choice of alternative fuels was based upon both calorific value and biodegradable fraction and it is assumed that they have low volatile heavy metal concentration. For instance, RDF consists largely of combustible components of municipal waste such as plastics and biodegradable waste. Moreover different criteria such as physical criteria (e.g. air entrainability), chemical criteria (e.g. chlorine, sulphur, alkali and phosphate content), reactivity and volatile metal content played a decisive role in the selection of alternative fuels, as these can have an impact on kiln operation and emissions.

In the operation phase of the kiln, all activities carried out and resources consumed during the operation are included. The assumed time horizon of the system is thirty years, which is the average life span of equipment (the types of kilns used for lime manufacture have a general lifetime of 30 to 45 years [12]). The life cycle impact assessment of this phase includes the quality and quantity of raw materials, fossil fuels, alternative fuels and energy inputs during the phase. However, the production of equipment, its maintenance and personnel are not accounted for due to the lack of representative data. Extraction and transportation of raw materials are included. The extraction and production of conventional fuels (coal and petcoke) as well as the extraction and production electricity used during the operation of kiln are also included. The energy requirements are calculated based on average electricity consumption.

Air emissions released from the production of clinker during the operation phase were calculated by using emission factors per ton fuel [38] and stoichiometric considerations.

The construction phase and all activities such as transportation of raw materials and construction of facilities, as well as resources (e.g. concrete, steel, gravel) consumed are not considered because their impacts are considered negligible. The production of vehicles and the equipment (kiln, pipe lines, storage silos etc) are excluded, because the impact of these activities is normally small, compared to contributions from operation phase. The exclusion of these factors does not limit the value of the approach, as these parameters are assumed to be equally important in all scenaria considered.

The production of clinker takes place in a rotary dry process kiln. It was assumed that the dry process plant, producing 1,500,000 tons of clinker per year at a specific thermal rate of 850 kcal/kg and includes two rotary kiln/preheater lines, with a baseline fuel corresponding thermally to 30% coal and 70% petcoke at blower capacity.

Data Inventory

The LCA software SimaPro 7.1 was used to evaluate the environmental impacts of inventory aspects and to the life cycles for seven scenaria. The data have been collected from various sources. Inventory data for raw material acquisition (mining of limestone, sandstone, iron ore etc), along with electricity production and heat generation by fuel type for the processing steps were obtained from the SimaPro libraries and databases. The energy demands for the production of raw materials have been obtained from the data bases BUWAL 250 [39] and ETH Energy version, incorporated in the SimaPro 7.1 software package [34]. The energy demands for transportation have been estimated by taking into account road transportation and a truck capacity of 28 tons (kg/km). Electrical energy in Greece is produced using four different sources, namely as lignite, oil, natural gas and hydropower [40]. The contribution of each source to the average national electricity mix, based on installed power (MW), is 43%, 19%, 13% and 25% respectively. However, hydropower is used only at peak times and in fact contributes only 10% to the total annual average electricity mix.

The term raw materials includes limestone, slate, flysch, sandstone, bauxide, fly ash, iron source and aggregates and the total quantity of raw material consumption is about 1,65 kg per ton of clinker and the electrical energy consumption amounts to 120kWH per ton of clinker.

The required quantities of raw materials for the production 1 ton of clinker and the inventory data of conventional fossil fuels (coal and petcoke) and alternative fuels (RDF, TDF and BS) are summarized in Tables 1 and 2 respectively.

Table 1-Required quantities of raw materials for the production 1 ton of clinker

Raw material	**Quantity (ton)**	**Raw material**	**Quantity (ton)**
Limestone	8.63E-01	Bauxide	2.30E-03
Slate	9.08E-02	Fly ash	1.80E-03
Flysch	5.00E-04	Fe source	1.82E-02
Sandstone	5.40E-03	Aggregates	2.00E-03

Table 2-Inventory data of conventional fossil and alternative fuels

	Conventional Fossil Fuels		Alternative Fuels		
	Coal	Petroleum coke (petcoke)	Refuse Derived Fuel (RDF)	Tire Derived Fuel (TDF)	Biological Sludge (BS)
NCV (kJ/kg dry fuel)	30000	33000	26000	32000	16000
Ultimate analysis mass % dry material					
C	7.50E+01	9.00E+01	5.30E-01	8.17E-01	4.05E-01
H	5.00E+00	3.74E-02	7.00E-02	7.84E-02	7.00E-02
O	8.00E+00	7.60E-03	2.10E-01	1.02E-02	3.26E-01
S	3.00E-01	4.34E-02	0.00E+00	1.81E-02	1.20E-03
N	1.00E-02	2.37E-02	1.00E-04	5.70E-03	8.40E-03
Cl	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.00E-02
P	0.00E+00	0.00E+00	1.90E-01	7.06E-02	0.00E+00
Slag	9.84E+00	5.80E-03	0.00E+00	0.00E+00	1.79E-01
Emission factors per ton of fuel					
CO_2	2.76E+00	3.23E+00	1.94E+00	3.00E+00	1.49E+00
H_2O	5.97E-01	5.01E-01	8.11E-01	9.42E-01	7.92E-01

O_2	4.70E-01	5.37E-01	4.02E-01	5.79E-01	2.67E-01
NOx	9.28E+00	1.06E+01	7.93E+00	1.14E+01	5.27E+00
SO_2	9.05E-02	1.08E-01	5.00E-04	2.61E-02	3.84E-02
HCl	3.20E-03	4.88E-02	0.00E+00	2.04E-02	1.40E-03
P_2O_5	0.00E+00	0.00E+00	4.35E-01	1.62E-01	0.00E+00

Environmental impact assessment

The emissions of each alternative integrated scenario were grouped into environmental impacts. For the environmental impact assessment, the CML 2 baseline 2000 methodology, World 1995 normalisation/weighting set and the Eco-indicator 99 methodology, available in SimaPro 7.1, were utilized. The impact categories considered in the CML 2 baseline 2000 methodology are the Abiotic Depletion Potential (ADP, kg Sb eq), the Global Warming Potential (GWP, kg CO_2 eq), the Ozone Layer Depletion (ODP, kg CFC-11 eq), the Human Toxicity Potential (HTP, kg 1,4-DCB eq), the Freshwater Aquatic Ecotoxicity Potential (FAETP, kg 1,4-DCB eq), the Marine Aquatic Ecotoxicity Potential (MAETP, kg 1,4-DCB eq), the Terrestrial Ecotoxicity Potential (TETP, kg 1,4-DCB eq), the Photochemical Oxidation (POCP, kg C_2H_4), the Acidification (AP, kg SO_2 eq) and the Eutrophication Potential (EP, kg PO_4 eq). As well as the main impact categories considered in the Eco-indicator 99 methodology are the Human Toxicity (Carcinogens, Respiratory effects Organics and Inorganics and Radiation), the Climate Change Effects, the Ozone Layer Depletion and the Ecosystem Quality (Ecotoxicity, Acidification and Eutrophication, Land Use and Fossil fuels).

RESULTS

Since clinker production is highly energy intensive, the use of alternative fuels (AFs) complying with the regulations is able to reduce the environmental impacts as well as to contribute to environmental protection, by decreasing the amount of fossil fuel needed to produce cement. The combustion of alternative fuels, in fact, has been proved to be an ideal method for recovering optimal heating power from waste and for reducing environmental impacts associated with clinker production. The results of the study described in this paper confirm the positive impact of this industrial option.

The substitution of conventional fuels by alternative fuels is limited to 10% of the required net calorific value (NCV) of conventional fuels for thermal needs of kiln operation. The results of seven alternative scenaria, in terms of relative contribution to the life cycle for each of the both CML 2 baseline 2000 methodology and Eco-indicator 99 methodology and to the main impact categories are presented in Table 3 (normalized environmental impacts). Furthermore, a comparison of the seven alternative scenaria of clinker production, in terms of relative contribution to the life cycle for each of the Eco-indicator 99 methodology and to main impact categories are shown in Figure 4.

Table 3 - Contribution of alternative scenarios 1-7 to main impact categories (per ton clinker)

Impact Category	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7
CML 2 baseline 2000							
Abiotic depletion	3.1105E+00	3.0662E+00	3.1295E+00	2.8766E+00	2.8766E+00	2.8766E+00	2.8766E+00
Acidification	1.5221E+01	1.4198E+01	1.5659E+01	1.4053E+01	1.4729E+01	1.3713E+01	1.4164E+01
Eutrophication	6.9995E-02	7.2269E-02	6.9023E-02	2.4721E+00	6.4798E-02	8.0370E+00	3.5212E+00
Global warming (GWP100)	4.9870E+02	4.9067E+02	5.0217E+02	4.8998E+02	4.8971E+02	4.8328E+02	4.8763E+02
Ozone layer depletion (ODP)	5.1087E-04	4.8829E-04	5.2057E-04	4.5903E-04	4.5903E-04	4.5903E-04	4.5903E-04
Human toxicity	1.5544E+02	1.4833E+02	1.5850E+02	1.4292E+02	1.4288E+02	1.4278E+02	1.4286E+02
Fresh water aquatic ecotox.	3.6970E+01	3.6230E+01	3.7288E+01	3.5211E+01	3.5211E+01	3.5211E+01	3.5211E+01
Marine aquatic ecotoxicity	1.0765E+05	1.0518E+05	1.0871E+05	1.0182E+05	1.0182E+05	1.0182E+05	1.0182E+05
Terrestrial ecotoxicity	1.1528E+00	1.1476E+00	1.1551E+00	1.1355E+00	1.1355E+00	1.1355E+00	1.1355E+00
Photochemical oxidation	6.1035E-01	5.6990E-01	6.2771E-01	5.6349E-01	5.9055E-01	5.4990E-01	5.6796E-01
Eco-indicator 99							
Carcinogens	1.0239E+00	1.0243E+00	1.0237E+00	1.0218E+00	1.0218E+00	1.0218E+00	1.0218E+00
Resp. organics	2.3400E-02	2.2900E-02	2.3600E-02	2.1300E-02	2.1310E-02	2.1310E-02	2.1310E-02
Resp. inorganics	1.8485E+01	1.7623E+01	1.8856E+01	1.7376E+01	1.7977E+01	1.7074E+01	1.7475E+01
Climate change	2.9503E+00	2.9165E+00	2.9649E+00	2.9161E+00	2.9150E+00	2.8886E+00	2.9064E+00
Radiation	2.5900E-02	2.5800E-02	2.5900E-02	2.5700E-02	2.5700E-02	2.5700E-02	2.5700E-02
Ozone layer	1.1100E-02	1.0600E-02	1.1300E-02	1.0000E-02	9.9900E-03	9.9900E-03	9.9900E-03
Ecotoxicity	1.1948E+00	1.1896E+00	1.1970E+00	1.1863E+00	1.1863E+00	1.1863E+00	1.1863E+00
Acidification/ Eutrophication	1.4943E+00	1.4325E+00	1.5209E+00	1.3994E+00	1.4452E+00	1.3764E+00	1.4070E+00
Land use	4.6980E-01	4.6850E-01	4.7040E-01	4.6680E-01	4.6675E-01	4.6675E-01	4.6675E-01
Minerals	3.1750E-01	3.1740E-01	3.1760E-01	3.1720E-01	3.1718E-01	3.1718E-01	3.1718E-01
Fossil fuels	3.0658E+01	3.0127E+01	3.0886E+01	2.8298E+01	2.8298E+01	2.8298E+01	2.8298E+01

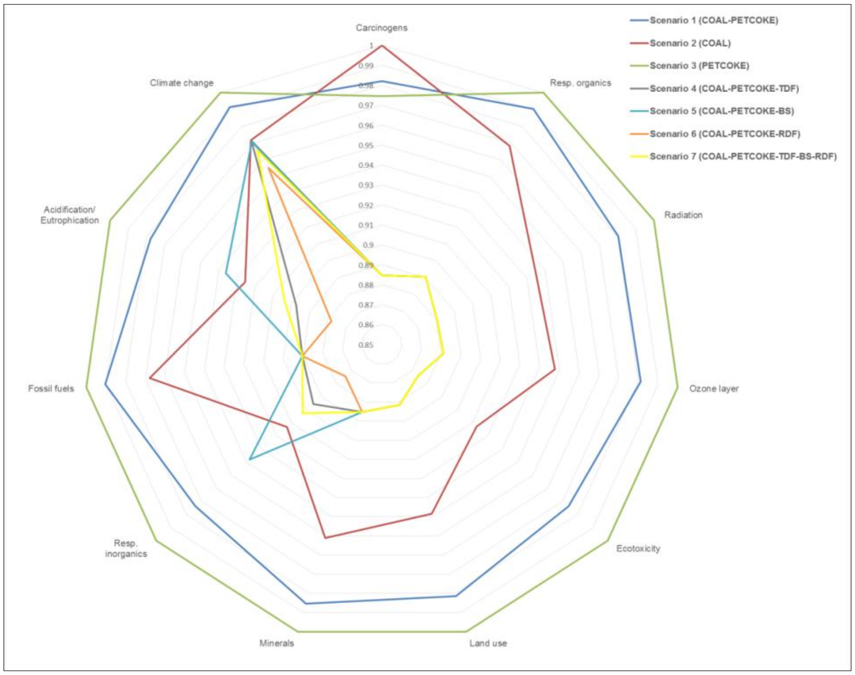

FIGURE 4 - Contribution of all scenaria to the impact categories (Eco-indicator 99 methodology), 10% substitution of conventional fossil fuels by alternative fuels

According to the results, alternative scenaria 1, 2 and 3, corresponding to the use of fossil fuels such as coal and petcoke, result in environmental pollution in all impact categories, while fossil fuels are non-renewable resources. In addition the use of petcoke (scenario 3) results in harmful environmental impacts. Comparing the scenaria with use of fossil fuels to alternative fuels, such as TDF, BS and RDF, it turns out that alternative fuels reduce the environmental impacts of all categories.

Figure 5 presents the relative contribution of each alternative integrated scenario of clinker production to the Global Warming Potential (GWP, kg CO_2 eq) impact category. From this figure it is evident that the use of Biological Sludge (BS) as alternative fuel (scenario 5) has the highest environmental impact in the life cycle of the process. Similarly Figure 6, which presents the contribution of each alternative scenario to the Photochemical Oxidation (POCP, kg C_2H_4) impact category, shows that scenario 5 is most harmful and scenario 6 optimal. It is worth noting that the BS as alternative fuel has a lower calorific value (16,000 kJ/kg dry fuel) compared to RDF and TDF. This results in higher required quantities of BS for the kiln operation needs. In addition the combustion of BS leads to emissions with notable concentrations of NO_X and SO_2. On the other hand, the use of RDF and TDF as alternative fuels has a smaller environmental impact, because their calorific value is higher (26,000 kJ/kg and 32,000 kJ/kg respectively).

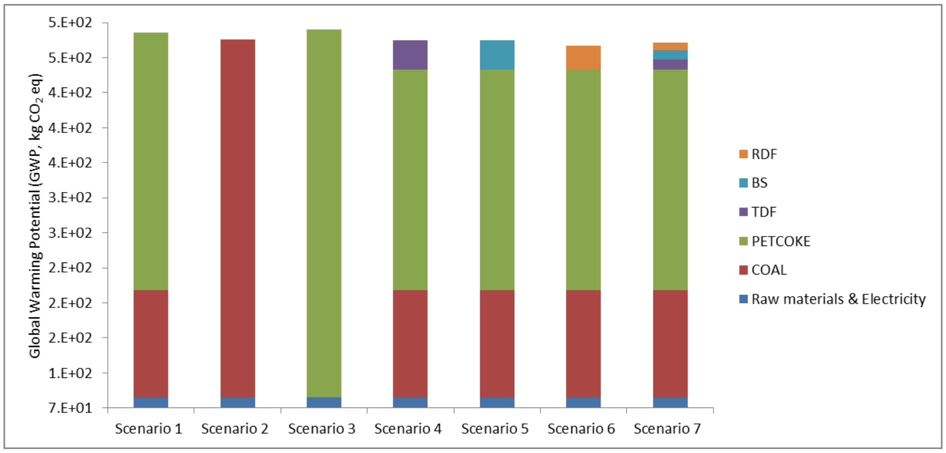

FIGURE 5-Contribution of all alternative scenaria to the impact category GWP (Global Warming Potential, kg CO_2 eq)

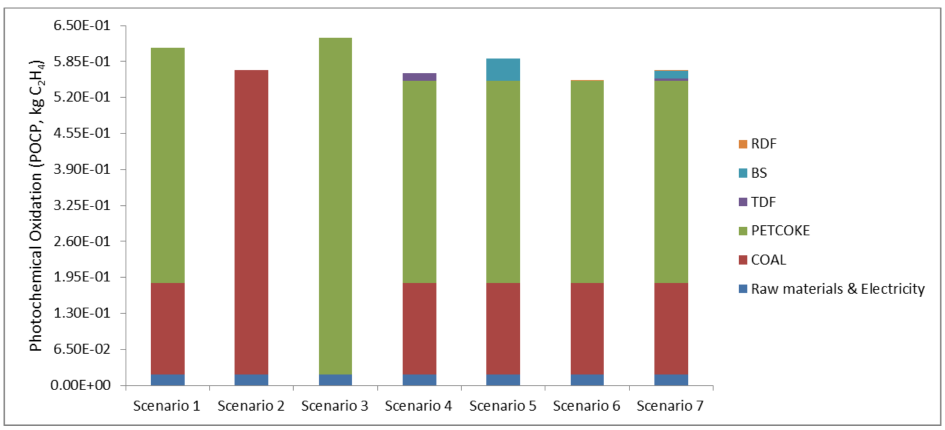

FIGURE 6-Contribution of all alternative scenaria to the impact category POCP (Photochemical Oxidation, kg C_2H_4)

In the sequel, a 30% (instead of 10%) substitution of conventional fossil fuels by alternative fuels was examined. In this case, the proportion of coal was considered constant, amounting to 30% in scenaria 4, 5, 6 and 7, similarly to the 10% substitution case. The proportion of petcoke was modified, so that the total contribution of fossil fuels corresponded to 70% of the total calorific value. The alternative fuels replace 30% of the total calorific value needed for the function of the kiln. The results of the seven alternative scenaria, in terms of relative contribution to the main impact categories are presented in Figure 7. The use of fossil fuels results in environmental pollution in all impact categories, while alternative fuels are more environmentally friendly. Figure 8 depicts the contribution of scenaria 4, 5, 6 and 7 to the impact category GWP for 10% and 30% substitution fossil fuels by alternative fuels. In addition, Figures 9 and 10 present the percent of reduction to the main impact categories when substitution is increased from 10 to 30%.

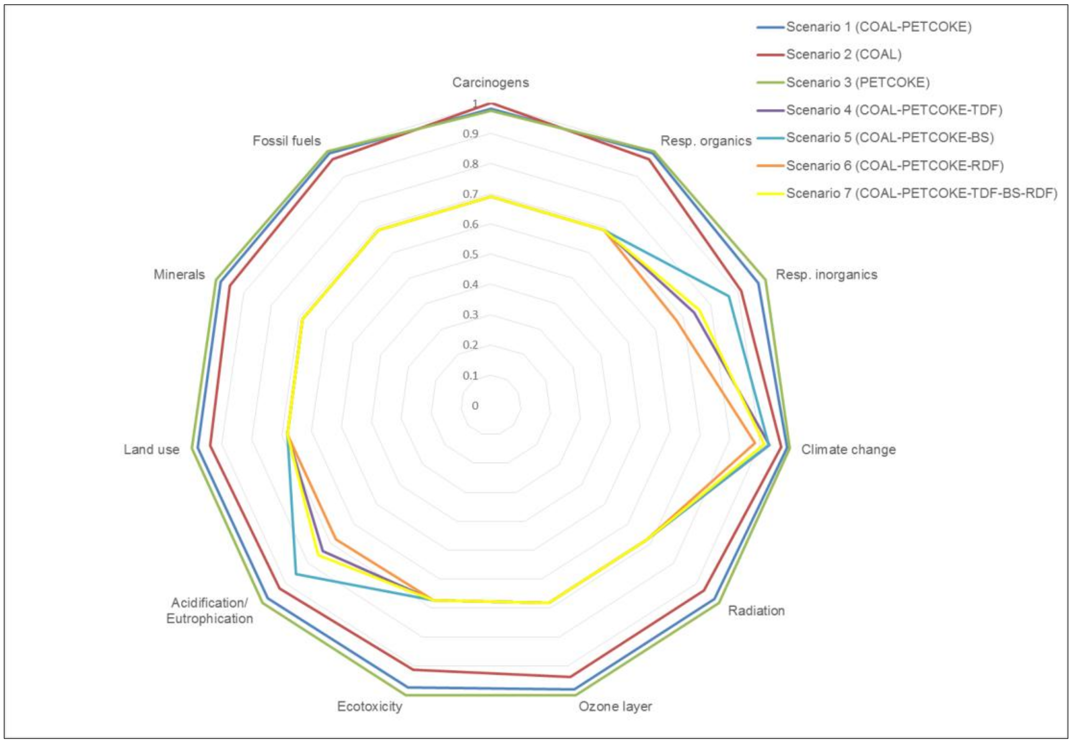

FIGURE 7 - Contribution of all alternative scenaria to the impact categories (Eco-indicator 99 methodology), 30% substitution of conventional fossil fuels by alternative fuels

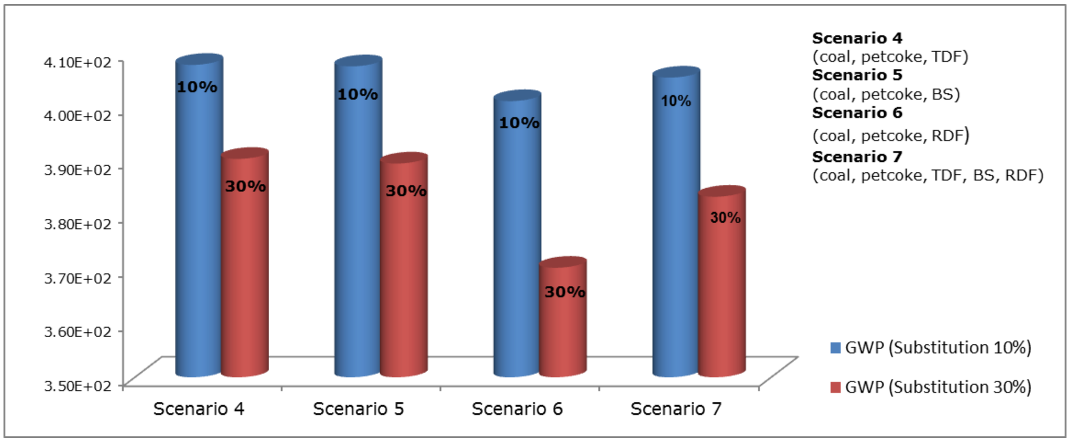

FIGURE 8 - Contribution of scenaria 4, 5, 6 and 7 to the impact category GWP for 10% and 30% substitution of fossil fuels by alternative fuels

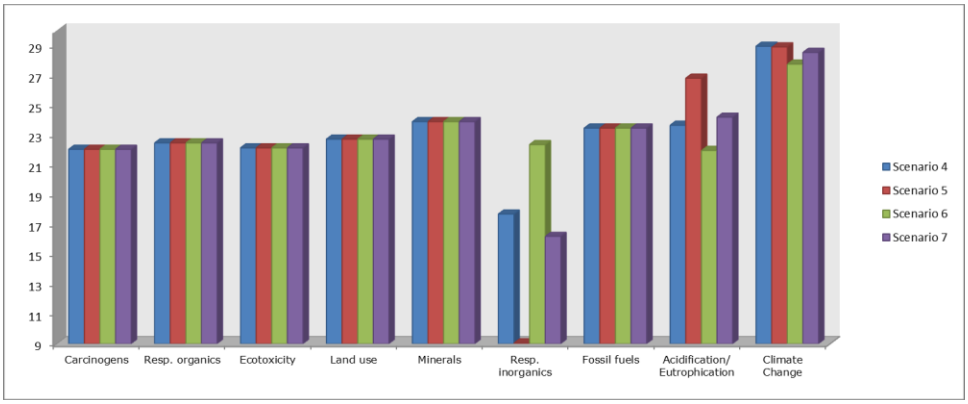

FIGURE 9 - Percent reduction of scenaria 4, 5, 6 and 7 to the impact categories of Eco-indicator 99 methodology when substitution is increased from 10 to 30%

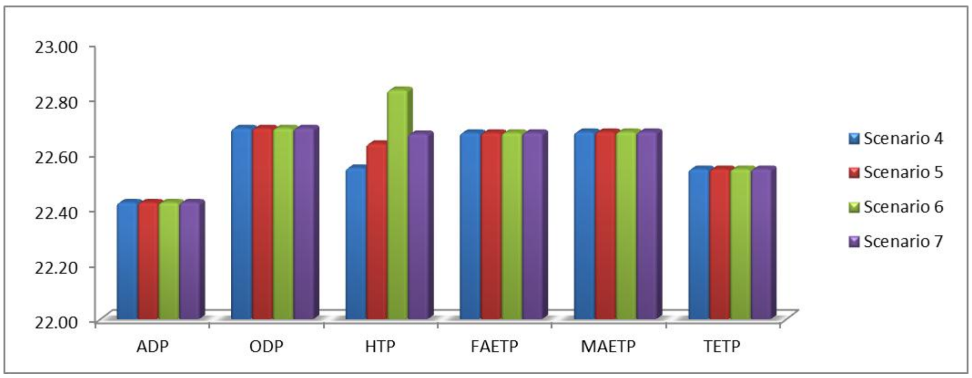

FIGURE 10- Percent reduction of scenaria 4, 5, 6 and 7 to the impact categories of CML baseline 2000 methodology when substitution is increased from 10 to 30%

Based on the overall results of the environmental impact assessment as presented in Figures 4-6 and Table 3 for 10% substitution of conventional fossil fuels by alternative fuels and Figure 7 for 30% substitution of conventional fossil fuels by alternative fuels, alternative scenaria 4, 5, 6 and 7 are better than scenaria 1, 2 and 3 respectively, while scenario 6 is the best. This means that the use of RDF as alternative fuel in the clinker production is the better option from an environmental point of view.

Analysing the values for each impact category (Figure 4), it can be highlighted that fossil fuels are responsible of the impact in all of the alternative scenaria. The study results also indicate that the substitution of conventional fossil fuels by alternative fuels such as RDF (Refuse derived fuel), TDF (Tire derived fuel) and BS (Biological sludge) or a mixture of them is environmentally friendly, resulting in fewer emissions and therefore environmental impacts. It should be noted that the use of RDF has an advantage when compared to the other alternative fuels.

Furthermore the emissions to air from the clinker production system depend on the nature and composition of fuels. The interpretation of the results provides the conclusion that the most environmentally friendly prospect is the scenario based on RDF while the less preferable scenario is the scenario based on BS.

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