Journal of Environmental Management xxx (2017) 1–11

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Life cycle assessment of the use of alternative fuels in cement kilns: A case study

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ARTICLE INFO

Article history:
Received 29 January 2017
Received in revised form
23 June 2017
Accepted 6 July 2017
Available online xxx

Keywords:
Alternative fuels
Life cycle assessment
Cement production
Clinker process

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 be degraded or 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.

1. Introduction

1.1. Cement production

Cement is an essential ingredient which fulfills basic needs such as the construction of housing and infrastructure indispensable 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 5–7% of the global CO_2 emissions, total CO_2 anthropogenic emissions and substantial emissions of SO_2, NO_X and other pollutants (Hendricks et al., 1998; Van Oss and Padovani, 2002, 2003; Humphreys and Mahasenan, 2002; EIPPCB, 2010; Ali et al., 2011; Karagiannidis, 2012). Numerous studies have been done to evaluate CO_2 emissions, energy consumption (Capros et al., 2001; CIF, 2003; and Gartner, 2004) and SO_2 emissions (Josa et al., 2004, 2007), using Life Cycle Assessment (LCA) method. Emission of CO, NO_X and SO_2 from the cement industry contributes severely to greenhouse and acid rain effects (Zhang et al., 2011). 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 (Boesch and Hellweg, 2010).

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 (Worrell et al., 2000; Chen et al., 2010a,b). Furthermore a recent study on the current status and the latest literature on the cement production indicate that there are differences in the estimation of the CO_2 emissions (5–8% of global CO_2 emissions) and the cement manufacturing sector contributes up to 8% of the total global anthropogenic CO_2 emissions (Mikulčić et al., 2016). According to this study, if one assumes that cement production generates a world-average carbon emission of 0.83 kg CO_2/kg cement produced (Teklay et al., 2015), multiplies it with the produced cement (Oh et al., 2014), and compares it to the total CO_2 emissions (IPCC, 2014) then it is found that cement production contributes up to 8% of the total global anthropogenic CO_2 emissions, a percentage

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http://dx.doi.org/10.1016/j.jenvman.2017.07.017

Please cite this article in press as: Georgiopoulou, M., Lyberatos, G., Life cycle assessment of the use of alternative fuels in cement kilns: A case study, Journal of Environmental Management (2017), http://dx.doi.org/10.1016/j.jenvman.2017.07.017

that is in correlation to the latest report on global CO_2 emission trends by Olivier et al. (2015).

Cement contains a material called clinker which is formed when the raw material limestone is burned at high temperatures in a cement kiln (Van Oss and Padovani, 2002). In this process (called calcination) calcium carbonate decomposes and CO and CO_2 emissions are produced (Chen et al., 2010a,b). Calcination is highly important from a climate perspective, since carbon bound in minerals is transformed to CO_2 (Huntzinger and Eatmon, 2009). 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 (Nadal et al., 2009; GTZ-Holcim, 2006). The clinker is then 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 (Gäbel et al., 2004). 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, which are necessary to heat the kiln. The emissions of CO_2 depend mainly on both the type of process and the fuel used (European Commission, BREF, 2010). For instance, in a typical dry process with five stages 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 (European Commission, BAT, 2013; Moya et al., 2010; Phair, 2006). In addition to CO_2, atmospheric emissions from cement plants include other pollutants such as particles, nitrogen oxides (NOx), sulphur dioxide (SO_2) and some minor pollutants (Schneider et al., 2011).

The clinker production process has large environmental impacts compared to raw material preparation and the final cement production process. These environmental impacts are attributed to the direct kiln emissions and to the production of the primary fuels. Moreover, direct kiln emissions are the principal contributor to five main impact categories: global warming, terrestrial ecotoxicity, photochemical oxidation, acidification and eutrophication (Chen et al., 2010a,b).

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 (Schneider et al., 2011; European Commission, BREF, 2010). 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 (Gäbel et al., 2004).

1.2. *Alternative fuels (AFs)*

Traditionally, coal has been used as 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 (Schneider et al., 2011). 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. 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 secure high energy efficiency (European Commission, BAT, 2013).

The clinker-burning process offers good conditions for using different types of waste materials, replacing parts of the conventional fuels. The typical types of waste fuels (hazardous and non-hazardous) that may be used include wood, paper and cardboard, textiles, plastics, processed fractions (e.g. RDF), rubber and tires, industrial sludge, municipal sewage sludge, animal meal and fats, coal and carbon waste, agricultural waste, solid waste (impregnated sawdust), solvents and related waste, oil waste and oily waste (Cembureau, 1997, 1999).

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 are emitted per ton of product (80% of the finished product is clinker) 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 (Cembureau, 1997, 1999). Furthermore according to Best Available Techniques (BAT), a Reference Document for the Production of Cement (European Commission, BAT, 2013), 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 of air, CO_2 from calcination of $CaCO_3$ and the 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 (Cembureau, 2009). 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 reusable or recoverable. Therefore, replacement of some conventional fossil fuels with alternative fuels brings both ecological and economic benefits (Mokrzycki et al., 2003). 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 managed as waste, 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 is incorporated and substitutes raw materials in the cement (Environmental Protection Agency, 2008).

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 and spent solvents). Because some materials

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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 (GTZ-Holcim, 2006).

The great potential for the cement industry to save energy and reduce greenhouse gas emissions (GHGs) is associated with the replacement of traditional fuels with carbon-neutral materials, such as agricultural biomass, municipal solid waste (MSW) or meat and bone animal meal (MBM). Waste materials can be introduced into the cement manufacturing process directly into the kiln or by following a gasification phase with the combustion of the produced gas. In both cases, specific considerations regarding regulatory requirements must be observed (Usón et al., 2013).

The basic criteria for a material to be considered as fuel are: physical state of the fuel (solid, liquid, gaseous), content of circulating elements (Na, K, Cl, S), toxicity (organic compounds, heavy metals), composition and content of ash and content of volatiles, calorific value ($\geq$14.0 MJ/kg), chlorine content (<0.2%) and sulphur content (<2.5%), polychlorinated Biphenyls (PCBs) content (<50 ppm), heavy-metals content (<2500 ppm - out of which: mercury (Hg) < 10 ppm, and total cadmium (Cd), thallium (Tl) < 100 ppm), physical properties (scrap size, density, homogeneity), grinding properties, moisture content and the emissions released (Rahman et al., 2015; Mokrzycki et al., 2003; Madlool et al., 2011).

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 (Cement Sustainability Initiative, 2014). 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 and avoiding materials that contain pollutants, such as mercury because kilns cannot retain them and frequently monitor emissions (European Commission, BAT, 2013).

The chemical composition of the alternative fuel is one of the factors which influence the cement manufacturer to choose a particular alternative fuel for their plant. For example the high carbon content, the high heating value and the low moisture content make Tyre Derived Fuel (TDF) one of the most used alternative fuels in cement industry around the world. Moreover, the heating values of tyre are higher than those of bituminous coal (Rahman et al., 2015). However, tyres have some limitations when they are introduced into the kiln directly, because of the large quantity of Zn that remains in the ashes, which can modify the cement composition dramatically. Due to this problem replacement ratios under 30% for the kiln fuel are suggested (Usón et al., 2013). The usage of Refuse Derived Fuel (RDF) as alternative fuel decreases CO_2 emissions about 1.16 kg per kg (Genon and Brizio, 2008), while the use of BS (Biological Sludge) reduces NO_X emissions (Environmental Protection Agency, 2008). Moreover, the production of RDF from energy-rich MSW materials diverted from landfills and its usage as a substitute for conventional fossil fuel in cement kilns can be an environmentally and economically viable waste-to-fuel strategy (Reza et al., 2013).

1.3. *Life Cycle Assessment (LCA)*

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 (Rebitzer et al., 2004; Pennington et al., 2004). LCA is standardized under ISO 14041 (1998), ISO 14042 (2000), ISO 14043 (2000), ISO 14040 (2006) and ISO 14044 (2006).

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 (Guinèe et al., 2000, 2001). 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.

Moreover, 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 (Gäbel et al., 2004; Boesch et al., 2009; Huntzinger and Eatmon, 2009).

A critical analysis of existing LCA studies on co-processing of waste-derived fuels (also called co-incineration) in cement kilns has been conducted by Jose-Luis Galvez-Martos and Harald Schoenberger. Under this analysis the published results of life cycle inventories and environmental impact assessment of the co-incineration of waste-derived fuels have been assessed, with the objective of evaluating their assumptions, implications, limitations and main conclusions obtained from the application of different methodology frameworks. According to the results of the study, the environmental performance of co-incineration of waste in cement plants depends on a number of factors, specifically the chosen functional unit, the methodological decisions, the system boundaries, the considered parameters, the assumptions, the sources of data and the allocation approach. Moreover a deeper understanding of the flows inside the process and methodologies considering local impact would be a required complement LCA (Galvez-Martos and Schoenberger, 2014). Also a practical analysis of the influence of the use of alternative materials in the cement industry, taking into account previously published research studies has been performed by Alfonso Aranda Usón and co-authors. The analysis focuses on the technical, economic, and environmental effects of the use of five solid wastes (municipal solid waste (MSW), meat and bone animal meal (MBM), sewage sludge (SS), biomass, and end-of-life tyres (ELT)), in the cement industry. According to the results of the study alternative fuels can be introduced into the cement manufacturing process in two different ways, by direct combustion or by following a gasification phase with the combustion of the producer gas in the cement (Usón et al., 2013).

1.4. *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

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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.

2. Materials and methods

2.1. 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 (PRé Consultants, 2008).

2.2. Functional unit

According to the recommendations by Boesch et al. (2009), Feiz et al. (2015a,b), Ammenberg et al. (2015) and García-Gusano et al. (2015), 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.

2.3. Boundaries of the system

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 Fig. 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. The potential environmental impacts of the transportation of both conventional fuels (coal and petcoke) and alternative fuels are not included in the definition of the system, since they will vary significantly depending on the particular location of the plant and the location of the fuel sources.

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.

2.4. Alternative scenaria of clinker production

Seven basic alternative scenaria (Fig. 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 0.0356 ton, 0.0431 ton and 0.0333 ton respectively.

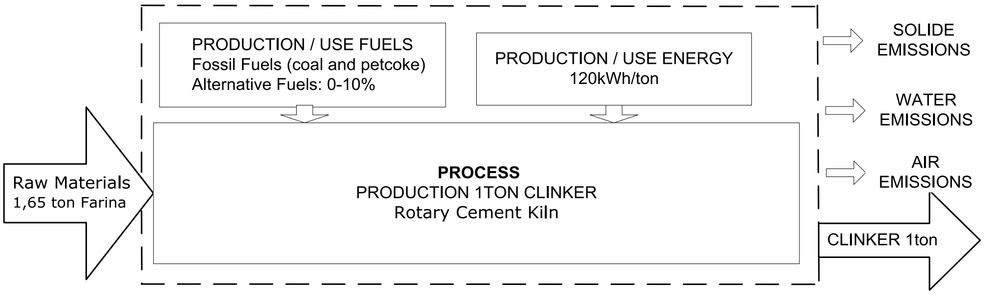

Fig. 1. Schematic flowchart of system - boundary analysis.

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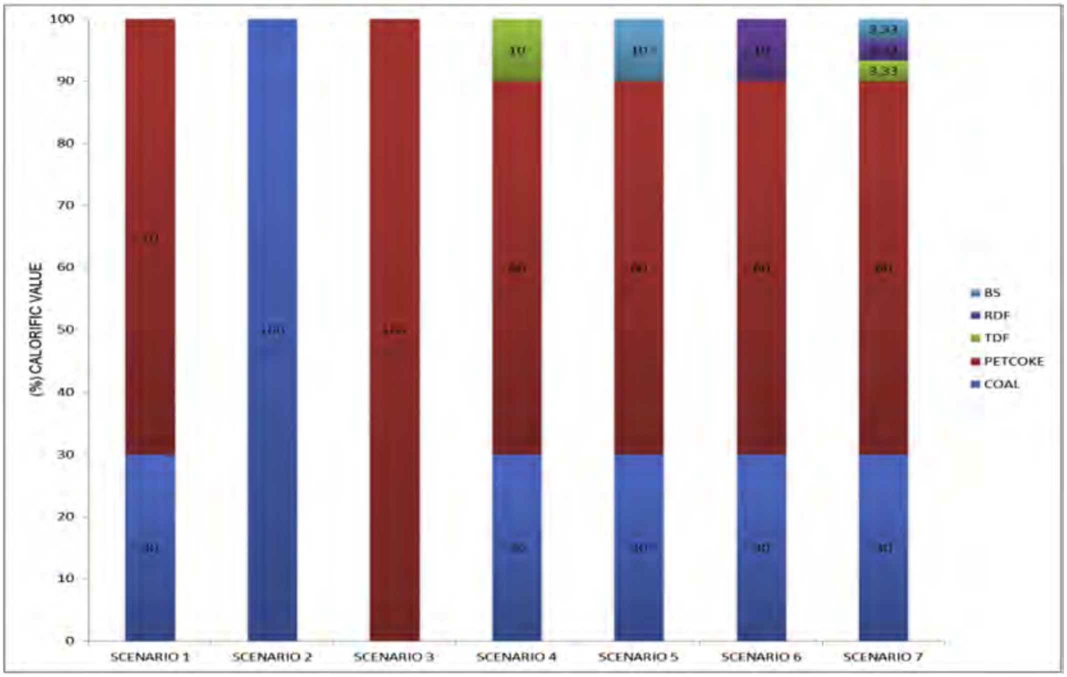

Fig. 2. Percentage of conventional fossil fuels (coal and petcoke) and alternative fuels (RDF, TDF and BS) per scenario.

- 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, 0.0431 ton 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. 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.

2.5. 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 (European Commission, BAT, 2013). Thus, the emissions of CO_2 are estimated to be 900–1000 kg/ton clinker, related to a specific heat demand of approximately 3500 to 5000 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 (European Commission, BAT, 2013). 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 1700 to 1800 MJ/ton clinker).

The choice of alternative fuels was based on both the calorific value and the 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. Heavy metal emissions from the cement industry are a significant environmental concern and need to be controlled through appropriate measures, hence it is necessary to consider the environmental impact from heavy metal concentration prior to adaptation and implementation of any alternative fuel (Rahman et al., 2015). Moreover different criteria such as physical criteria (e.g. air entrain ability), 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 30–45 years (European Commission, BAT, 2013)). 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

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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	Bauxite	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

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 (Tsiliyannis, 2012) and stoichiometric considerations (Kookos et al., 2011).

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, etc.) 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.

2.6. *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 (1996) and ETH Energy version, incorporated in the SimaPro 7.1 software package (PRé Consultants, 2008). 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 lignite, oil, natural gas and hydropower (P.P.C., 2006). 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, bauxite, 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 120 kWh 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.

2.7. *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).

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

Please cite this article in press as: Georgiopoulou, M., Lyberatos, G., Life cycle assessment of the use of alternative fuels in cement kilns: A case study, Journal of Environmental Management (2017), http://dx.doi.org/10.1016/j.jenvman.2017.07.017

Table 3
Contribution of alternative scenaria 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

3. 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 for cement production. 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.

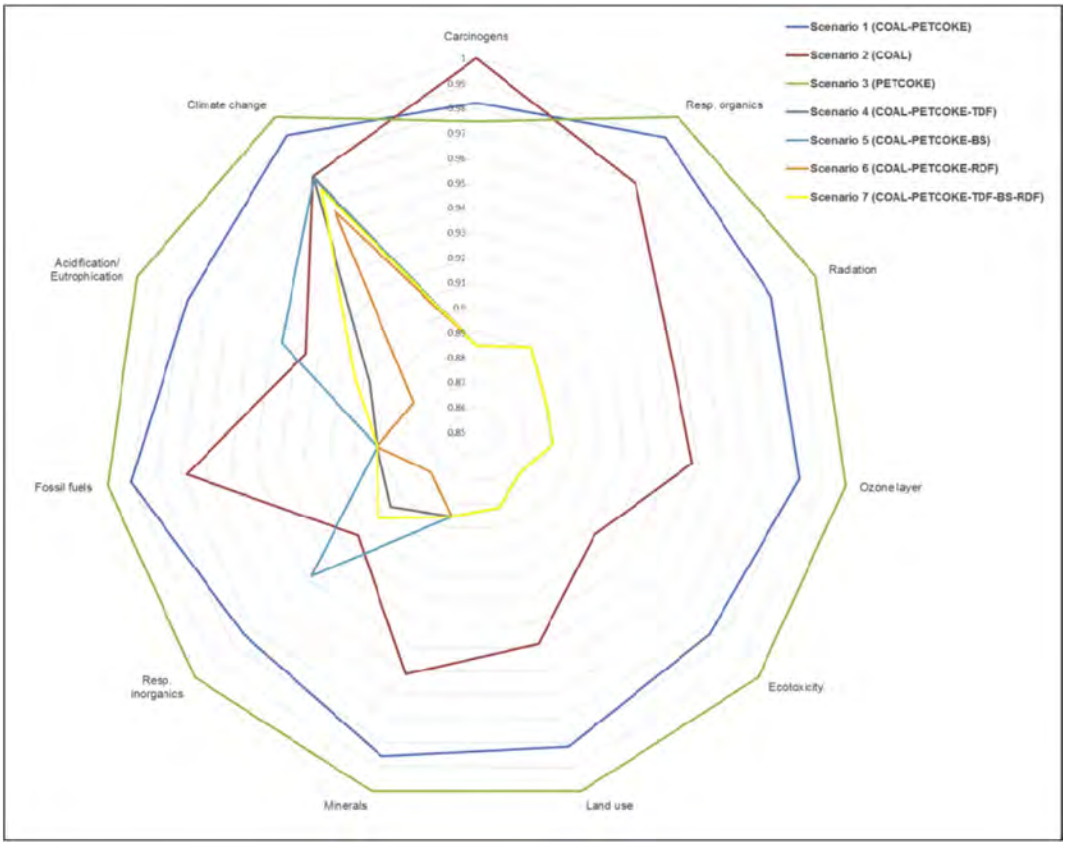

Fig. 3. Contribution of all scenaria to the impact categories (Eco-indicator 99 methodology), 10% substitution of conventional fossil fuels by alternative fuels.

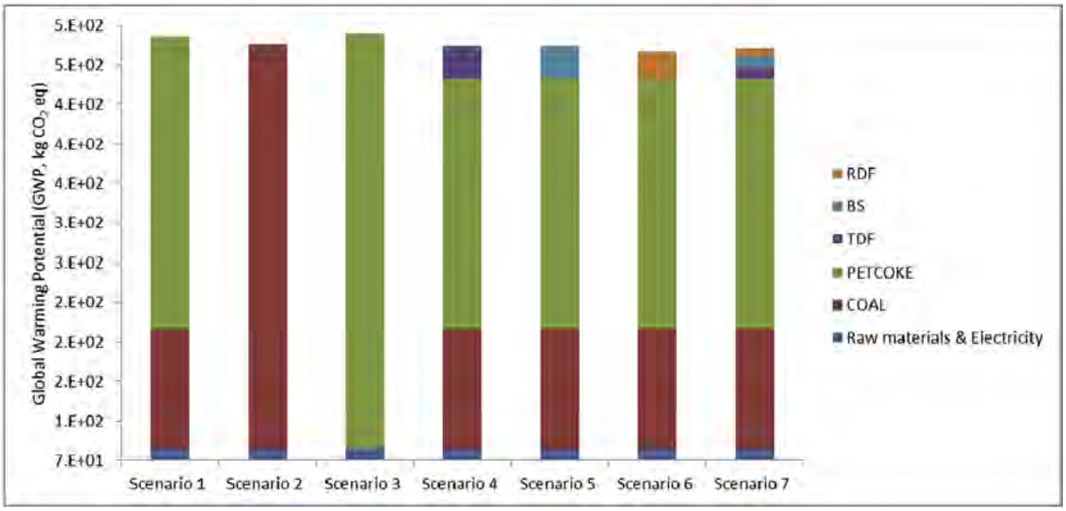

Fig. 4. Contribution of all alternative scenaria to the impact category GWP (Global Warming Potential, kg CO_2 eq).

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 both of the CML 2 baseline 2000 methodology and Eco-indicator 99 methodology, and the main impact categories are presented in Table 3 (normalized environmental impacts). A comparison of the seven alternative scenaria of clinker production, in terms of relative contribution to the life cycle of each main impact category of the Eco-indicator 99 methodology is shown in Fig. 3.

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.

Fig. 4 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, as far as the contribution of each alternative scenario to the Photochemical Oxidation (POCP, kg C_2H_4) impact category is concerned, scenario 5 is the most harmful and

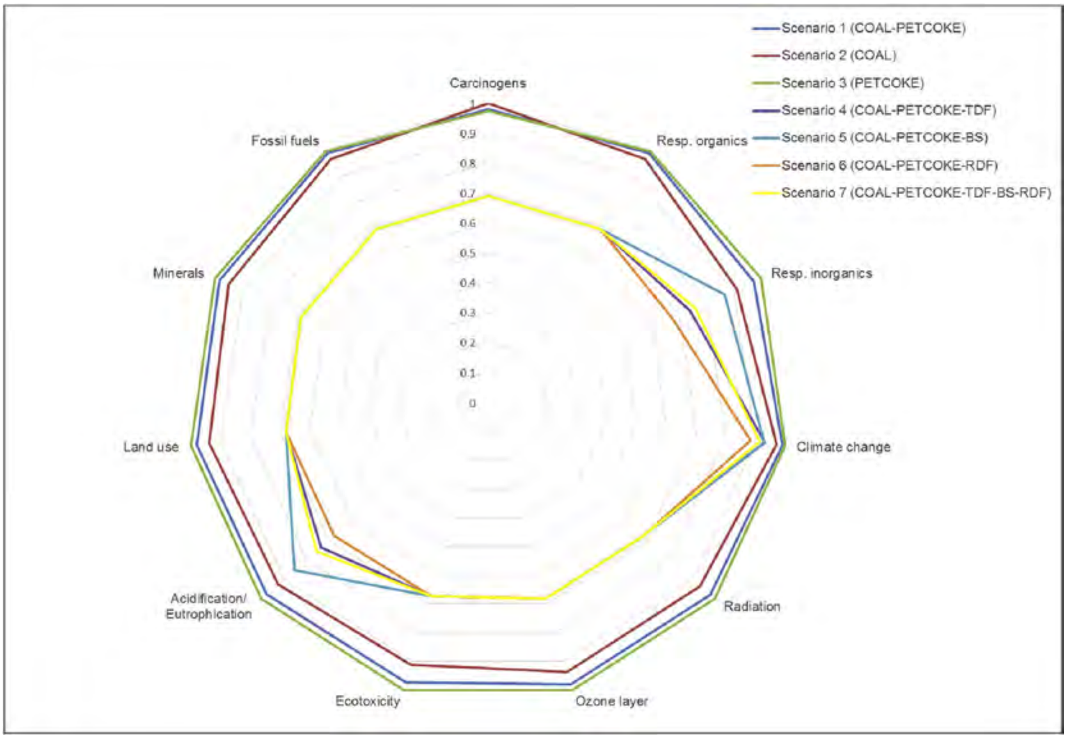

Fig. 5. Contribution of all alternative scenaria to the impact categories (Eco-indicator 99 methodology), 30% substitution of conventional fossil fuels by alternative fuels.

Please cite this article in press as: Georgiopoulou, M., Lyberatos, G., Life cycle assessment of the use of alternative fuels in cement kilns: A case study, Journal of Environmental Management (2017), http://dx.doi.org/10.1016/j.jenvman.2017.07.017

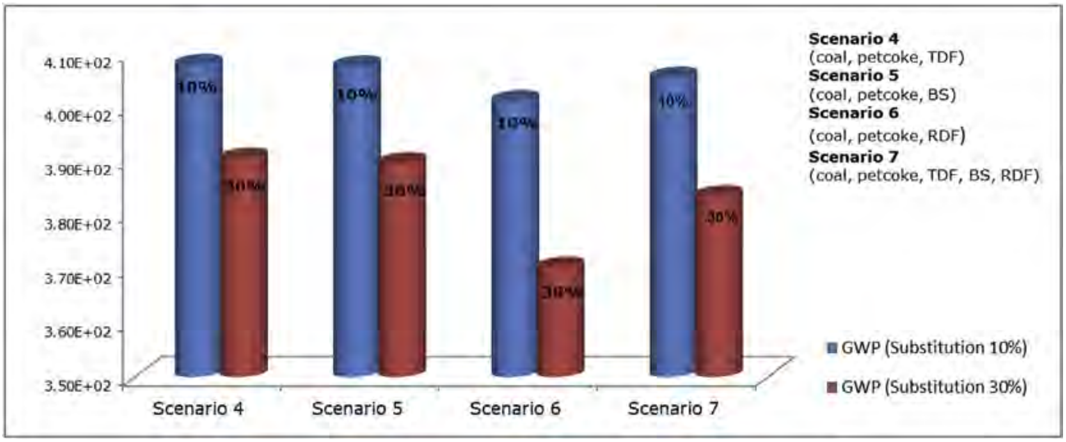

Fig. 6. Contribution of scenaria 4, 5, 6 and 7 to the impact category GWP for 10% and 30% substitution of fossil fuels by alternative fuels.

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).

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 Fig. 5. The use of fossil fuels results in environmental pollution in all impact categories, while alternative fuels are more environmentally friendly. Fig. 6 depicts the contribution of scenaria 4, 5, 6 and 7 to the impact category Global Warming Potential (GWP, kg CO_2 eq) for 10% and 30% substitution fossil fuels by alternative fuels. In addition, the percent of impact reduction of scenaria 4, 5, 6 and 7 is about 22.45% to the category of Abiotic Depletion Potential (ADP), 22.70% to the categories of Ozone Layer Depletion (ODP), Freshwater Aquatic Ecotoxicity Potential (FAETP), Marine Aquatic Ecotoxicity Potential (MAETP) and Ecotoxicity and 24% to the category of Fossil Fuels.

Based on the overall results of the environmental impact assessment as presented in Figs. 3 and 4 and Table 3 for 10% substitution of conventional fossil fuels by alternative fuels and Fig. 5 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 (Figs. 3 and 5), 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 the 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 least preferable scenario is the scenario based on BS.

4. Conclusion

A methodology for the evaluation of 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 petcoke, taking into account environmental considerations, was developed. Seven different scenaria were considered for the production of 1 ton of clinker in a rotary cement kiln. A spreadsheet model was developed and used to estimate the design inventory data from the operation phase of all alternative scenaria. The Life Cycle Assessment (LCA) methodology was used to quantify the potential environmental impacts for each scenario.

The interpretation of the results provides the conclusion that the most environmentally friendly prospect is the scenario based on RDF, while the least preferable is the scenario based on BS.

The final outcome of this work can be of use to engineers involved in the cement industry, local authorities (especially scientists involved in decision-making) and practitioners of LCA.

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Please cite this article in press as: Georgiopoulou, M., Lyberatos, G., Life cycle assessment of the use of alternative fuels in cement kilns: A case study, Journal of Environmental Management (2017), http://dx.doi.org/10.1016/j.jenvman.2017.07.017

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