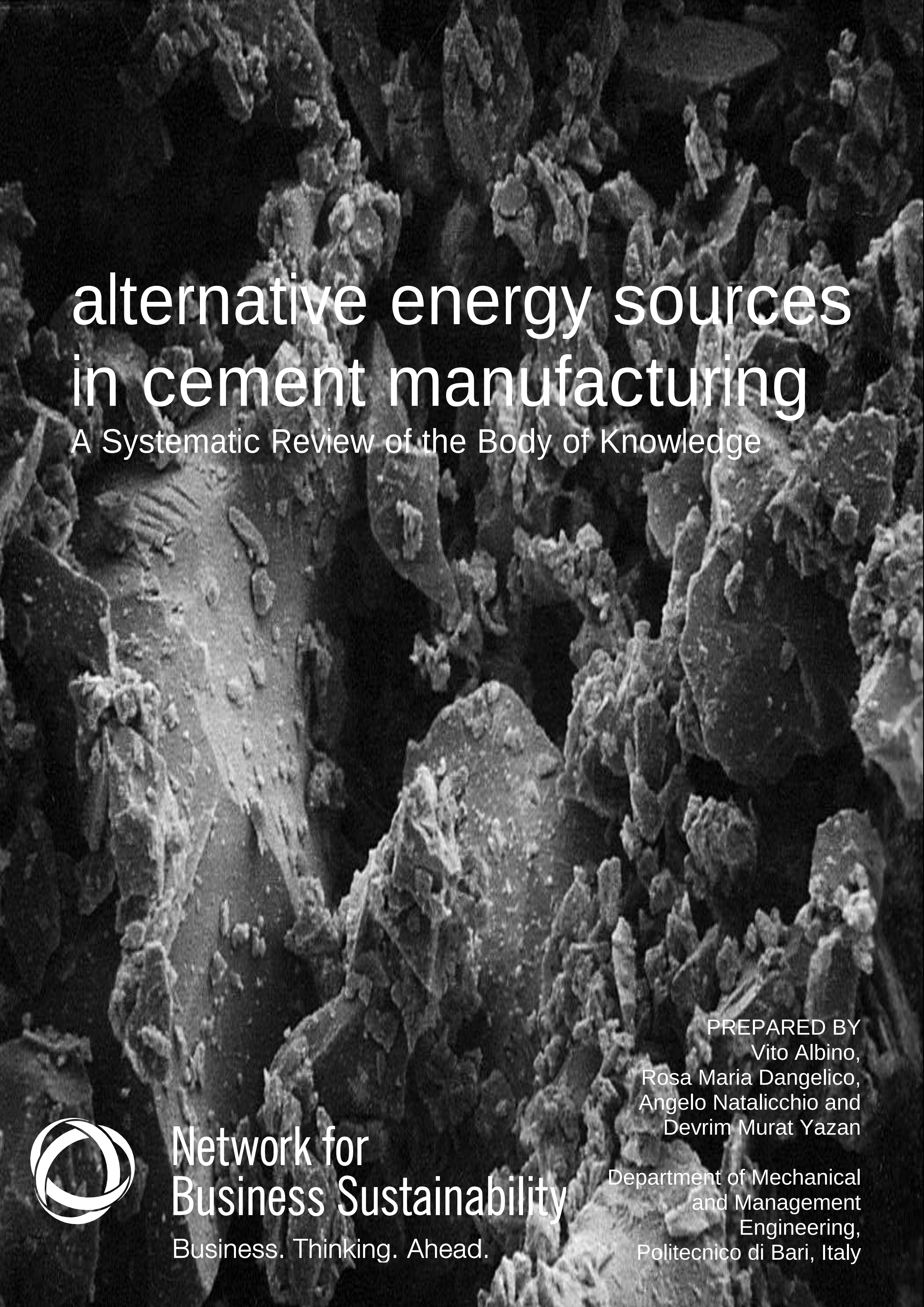

alternative energy sources in cement manufacturing

A Systematic Review of the Body of Knowledge

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Network for Business Sustainability
Business. Thinking. Ahead.

Dear Reader,

I am pleased to share the Network for Business Sustainability's report on the use of alternative fuels for manufacturing cement. With increasing urbanization, cement serves quite literally as the foundation of the building boom. It is an important driver of economic progress in most countries. In Canada, where this research was conducted, the cement industry contributes more than $3 billion annually to GDP and employs more than 25,000 workers. The amount and type of fuel consumed in producing cement not only impacts costs, but has social and environmental consequences.

This report address two questions: What are the environmental, social and economic impacts of using alternative fuels compared with conventional fuels in cement manufacturing? And, how does the use of alternatives in cement manufacturing compare with other possible end-of-life options like recycling or disposal in landfills?

Researchers Vito Albino, Rosa Maria Dangelico, Angelo Natalicchio, and Devrim Murat Yazan from the Department of Mechanical and Management Engineering, Politecnico di Bari, Italy systematically reviewed prior research to answer these questions. Systematic reviews collate, analyze and synthesize the body evidence from both academia and practice on a topic. As a result, they provide a powerful tool in moving forward research, business practice and public policy. For this review, the research team identified 110 prior studies from academic, institutional and practitioner sources that addressed the research questions.

The Network for Business Sustainability commissioned this systematic review for the Cement Association of Canada. We want to thank the committee that guided the research team, which was composed of Professors Doug Hooton and Heather MacLean from the University of Toronto, Luc Robitaille from Holcim Canada and John Cuddihy from the Cement Association of Canada. The research was subjected to double-blind peer review by three experts from academia and industry in Canada, the U.S. and Europe. Our sincere thanks go out to these contributors.

I am excited about this report, as this research has the opportunity to inform policy—and to drive change—in a meaningful way. While the report is quite technical, we hope it will shed light on a contentious issue in the cement industry. For those in other industries, we hope that it serves as a reminder of the challenges of managing complex, controversial issues and the role that rigorous evidence can play in informing collaborative discourse.

Tima Bansal, PhD
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1

introduction

This report aims to synthesize the available literature and research with respect to the use of alternative fuels in cement manufacturing. It reviews not only the environmental, social, technical, and economic impacts of using alternative fuels in cement kilns, but also compares alternative fuel use with other end-of-life options. It outlines how the use of alternative fuels in cement manufacturing could improve the industry's overall competitiveness, while reducing the industry's costs and the greenhouse gas (GHG) emissions associated with the manufacture of cement.

Documents used for this analysis include academic papers, institutional and practitioner reports, and case studies. Following the literature review, the findings extracted were used to create summary tables that can be used by policy makers, practitioners and other stakeholders.

This report is intended primarily for policy makers and practitioners already familiar with the cement manufacturing industry. However, this report will also be useful to other stakeholders, including the cement industry itself, academic and research institutions, and environmental organizations.

This study was based on the following research questions:

1. What are the environmental, human health, social, and economic implications of using alternative energy sources compared to the use of traditional fossil fuels (i.e., coal, petroleum coke) in cement manufacturing?
2. Considering the net environmental, human health, social and economic aspects, how does the use of alternative energy sources in cement manufacturing compare with other end-of-life / waste management options such as reuse, recycling, energy recovery, or disposal?

These research questions will henceforth be addressed, respectively, as RQ1 and RQ2.

1.1. Background

Cement manufacturing is an energy-intensive process with thermal and electric energy typically accounting for 40% of operational costs (European Commission, 2010). Fossil fuels, such as coal and petroleum coke, have traditionally been used as energy sources in the cement manufacturing industry; however, in recent decades, these fuels are increasingly being substituted with alternative, typically residue-based sources (e.g., sorted municipal solid waste, tires, and waste wood).

According to such institutions as the U.S. Environmental Protection Agency, the UK Health Protection Agency and the World Business Council for Sustainable Development, using alternative fuels in cement manufacturing could improve the environmental and the economic performance of the industry. The practice has yet to find broad acceptance by Canadian regulators and stakeholders, even though Canadian cement plants have used alternative fuels since the 1970s. A review of the relevant literature shows that there is a wide range of information regarding the impact of substituting fossil fuels with alternative fuels but, to date, this information has not been systematically collected and synthesized. The purpose of this document, therefore, is to provide a useful review of this literature to stakeholders.

1.2. Cement Manufacturing Industry & Alternative Energy Sources

As the main component of concrete, the production of cement plays a crucial role in Canada's economic development. In 2008, the industry contributed more than $3.2 billion to Canada's GDP, employed 27,000 workers (CAC, 2010a), and produced close to 13.7 million metric tonnes of cement (Statistics Canada, 2010).

Canada's cement manufacturing industry is concentrated in Ontario where roughly 50% of the national capacity is located, followed by Quebec (17%), British Columbia (16%), Alberta (14%), and Nova Scotia (3%) (Venta, 2007). Ontario's 2008 cement production was valued at $635 million (Ministry of Northern Development, Mines and Forestry, 2009).

However, cement production is an energy and carbon-intensive process, accounting for 5% of global man-made carbon dioxide (CO_2) emissions (includes the CO_2 generated from the decomposition or calcination of limestone and the emissions generated by heating the kilns) (WBCSD, 2009). In 2008, the average energy consumption of the Canadian cement industry was 4.09 GJ/metric tonne of cement (3.57 GJ/metric tonne of cement of thermal energy) (CAC, 2010b).[1]

[1] The manufacture of Portland cement involves the grinding and blending of clinker with small quantities of limestone and additives (e.g., gypsum). The manufacture of blended cements includes the blending and/or intergrinding of clinker, limestone, additives and other mineral components such as fly ash, slag, pozzolans, etc., which are also known as supplementary cementing materials (SCMs). In different regions of the world, the blending of SCMs occurs at different points in the product chain. For example, in Europe, much of the blending occurs at the actual cement manufacturing facility whereas in North America, much of the use of SCMs occurs downstream with the ready-mix concrete manufacturers. As such, care must be taken in comparing intensity figures from different regions in the world to ensure that a direct comparison of like products is being made. The energy intensity figures quoted here refer exclusively to Portland cement and blended cements produced directly at the cement facility and exclude direct sales of SCMs and downstream use of SCMs (line 21 of the WBCSD Cement CO_2 Protocol).

The sustainability of cement manufacturing, therefore, should be evaluated within the context of triple-bottom-line (3BL) thinking, i.e., integrating the 'three Ps' of profit, people, and the planet into the culture, strategy, and operations of companies (Kleindorfer et al., 2005). Using 3BL as its framework, 10 cement manufacturers launched in 1999 the Cement Sustainability Initiative (CSI) to manage the environmental, social, and health-related impacts associated with cement manufacturing. Nowadays, the world's 23 largest cement manufacturers (Italcementi, Holcim, Ashgrove, Lafarge, etc.) are members of the CSI (WBCSD, 2007). One of the CSI's strategies includes promoting the use of alternative energy.

Thermal energy substitution in Canadian cement manufacturing was 11.3% in 2008 (CAC, 2010b), a relatively small percentage compared to the almost 30% fossil fuel substitution found in countries such as Germany, France and Belgium (Sarkesian, 2006). Globally, the absolute volume of alternative fossil fuel use has grown at a compound annual rate of 10% in the last half decade (WBCSD, 2008). While Quebec mirrors the global rates, with a thermal energy substitution rate of 34.3%, it is far ahead of British Columbia (9.5%), Nova Scotia (8.0%), and Ontario (5.3%). Alberta has a 0% thermal energy substitution rate (CAC, 2010b). In 2006, of the nine Canadian cement plants using alternative fuels, only one was located in Ontario (Sarkesian, 2006).

In considering the net benefit of the use of alternative energy sources, several issues must be taken into account, such as the availability of technologies, CO2 emission reduction, economic viability, and potential environmental and health impacts.

For example, basic product quality requirements must be considered before using waste as an alternative fuel in cement manufacturing. Waste materials cannot always be combusted in the plant as they are received and a pre-processing stage must often be completed to transform the waste to fit the administrative and technical specifications of the kilns (Holcim, 2006). As a rule of thumb, waste accepted as fuel must supply calorific and/or material value to the cement kiln. Other important characteristics of the alternative fuel being considered include the water content, ash content, and concentration of sulphur, chlorine, and heavy metals, all of which can affect the overall performance of the cement plant (European Commission, 2010). Moreover, such alternative sources may have other potential uses (e.g., for use in recycling, remanufacturing, etc.), so it is important to understand the comparative advantages and disadvantages of their use in cement manufacturing.

In order to decrease the environmental impact of the industry, improve the competitiveness of cement companies, and provide a viable and convenient end-of-life option for waste and industrial by-products, the use of alternative fuels to obtain thermal energy in cement manufacturing is growing.

The most common alternative fuels used are:

- Municipal solid waste (MSW)
- Industrial, commercial & institutional (IC&I) residues
- Plastics
- Sewage sludge / biosolids
- Animal / bone meal, specified risk material
- Waste wood
- Used tires
- Other biomass

The use of any of these energy sources has environmental, economic, social, and health-related implications. Details about each fuel source are provided in Section 3.

1.3. Objectives

The objective of this report is to systematically review and synthesize the best and most reliable available research on the environmental, social and economic benefits and drawbacks of using alternative energy sources in cement manufacturing, and to compare possible end-of-life management options for materials that could be considered as alternative fuels in cement kilns.

As such, the literature review included available information related to the use of alternative energy sources in cement manufacturing. In particular, studies related to the environmental, health, social, and economic costs and benefits of the use of alternative sources compared to the use of traditional fossil fuels were analyzed. Moreover, the literature on the other possible end-of-life strategies (e.g., reuse, recycling, landfill disposal, etc.) for the alternative energy sources, compared with their combustion in cement kilns, was also reviewed and their comparative performance evaluated.

These research questions will henceforth be addressed, respectively, as RQ1 and RQ2.

1.4. Project Approach

This section discusses the methodology used to answer the research questions. Additional details are available in subsequent sections.

1.4.1. Overall Approach

The first step of the project was the literature assessment. The relevant documents were retrieved from academic databases, institutional and practitioner reports, and case studies and different research strings were used for different document repositories in order to fit the research to the particular typology of document. A list of data sources is available in Appendix 7.2.

These documents were then assessed to ensure their relevance to the project and to select the best ones for the goals of the research. The most relevant documents were then deeply analyzed, and their findings extracted and collected in tables that cross-reference each alternative fuel with each impact category considered. This was the starting point of the synthesis in order to create summary tables, the final deliverable of the project.

Several impact categories were used to classify the findings for both RQ1 and RQ2.

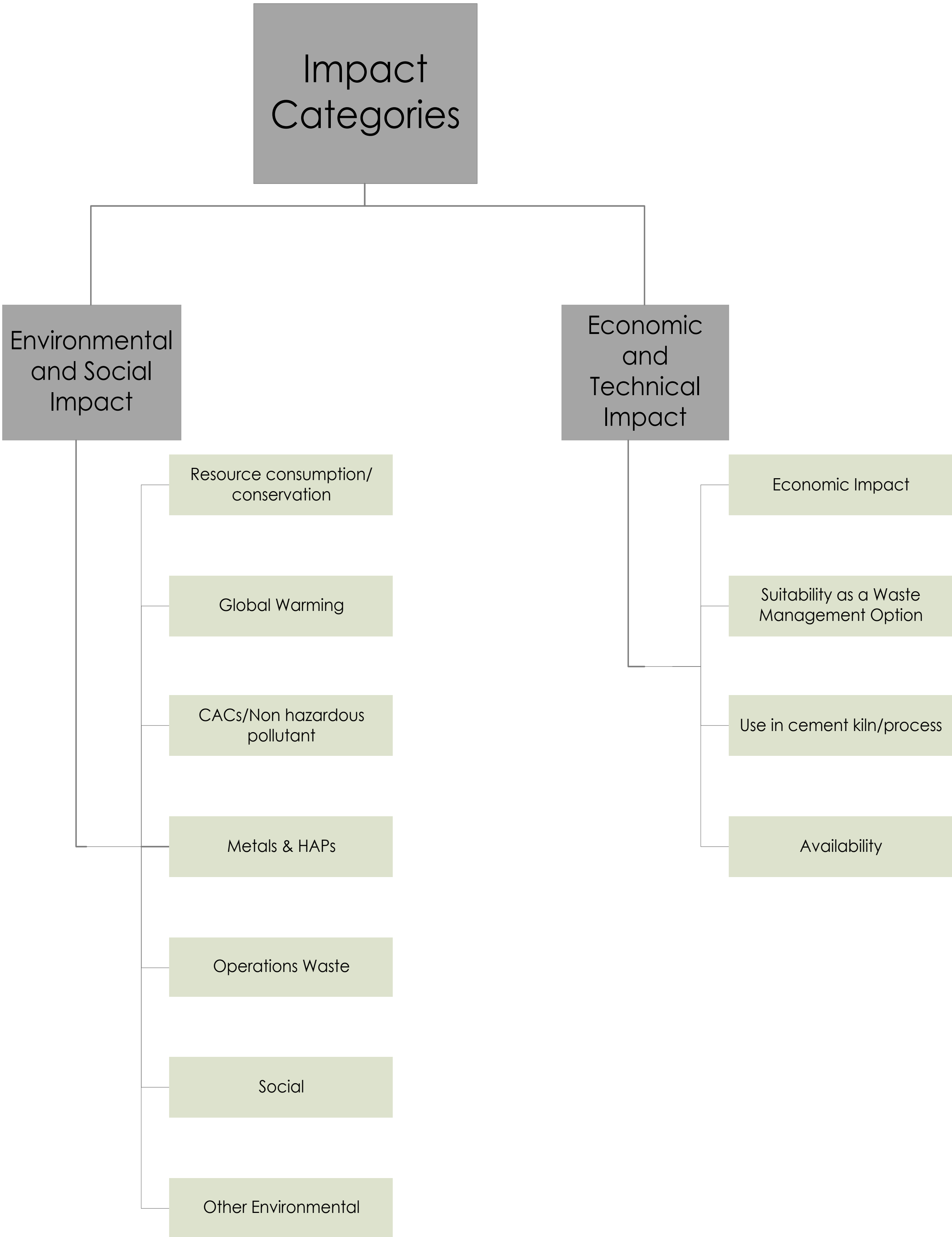
RQ1 findings were classified according to the following impact categories (see also Figure 1.1):

- **Environmental and Social Impact:** Impacts on the environment or on the communities affected by the use of alternative fuels
    - Resource consumption/conservation: The impact on consumption of fossil fuels or of raw materials
    - Global warming: The impact on the global climate as estimated through GHG emissions (primarily carbon dioxide)
    - Criteria Air Contaminants (CACs) / Non-hazardous pollutants: The impact on CACs (sulphur oxides, nitrogen oxides, particulate matter, carbon monoxide, ozone, except lead considered as metal) and non-hazardous air pollutants
    - Metals and Hazardous Air Pollutants (HAPs): The impact of emissions from metals (mercury, thallium, chromium, lead, copper, cadmium, zinc, barium, chlorine, nickel, arsenic, antimony, and beryllium) and HAPs (dioxins, furans, hydrogen chloride, hydrogen fluoride, volatile organic compounds, and polycyclic aromatic hydrocarbons)
    - Operations waste: The amount, hazardousness and reuse potential of waste generated (or reduced) during the combustion of alternative fuels in cement kilns and during the handling, storage, and processing stages
    - Social: The impact on community health, income, risk perception and acceptance
    - Other Environmental: Any other environmental impact not included in the previous categories, e.g., water pollution, acidification, and eutrophication

- **Economic and Technical Impact:** These categories relate to the profitability and technical aspects of using alternative fuels
    - Economic Impact: The impact on costs to cement plants, including both increased and avoided costs
    - Use in Cement / Kiln Process: The general impact of using alternative fuel in cement kilns, including pre-processing, handling, storage, safety measures, additional equipment, kiln modification, and other similar issues
    - Availability: The availability of alternative fuels for cement kilns

Figure 1.1

IMPACT CATEGORIES FOR RQ1

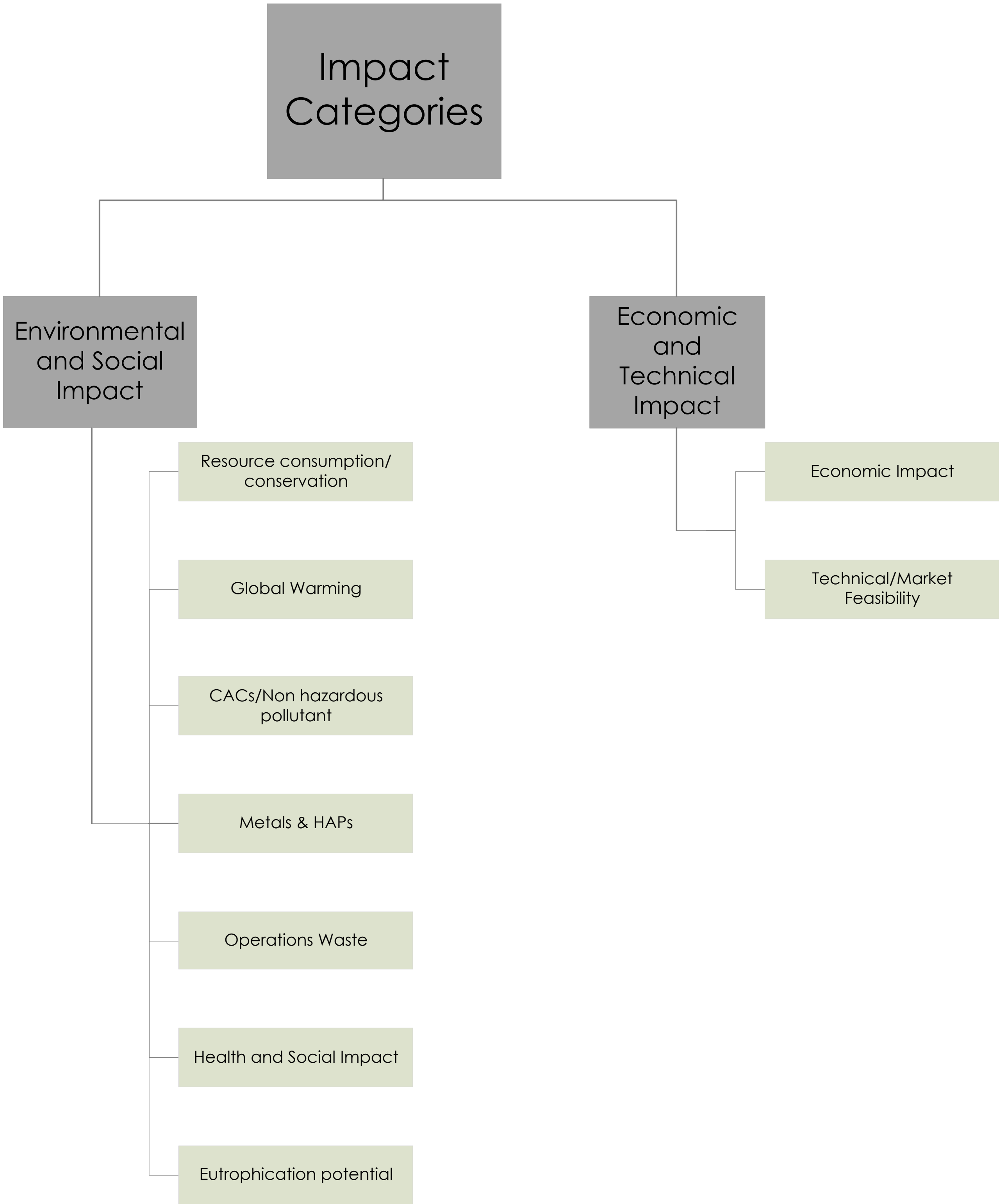


RQ2 findings were classified according to the following impact categories (see also Figure 1.2):

- **Environmental and social impact**
    - Resource consumption / conservation
    - Global warming
    - CACs / Non-hazardous pollutants
    - Metals & HAPs
    - Operations Waste
    - Health and social impact: The impact on human health and community income, risk perception and acceptance
    - Eutrophication potential: The potential of excess nutrients in receiving water bodies that can trigger excessive plant growth
- **Economic and technical impact**
    - Economic impact
    - Technical / market feasibility: The level of feasibility and market acceptance of the end-of-life management options.

Figure 1.2

IMPACT CATEGORIES FOR RQ2



1.4.2. Analytical Approach

As indicated above, this study takes into account both life-cycle assessment (LCA) and non-LCA literature. Non-LCA studies were analyzed and the main findings that emerged were grouped by impact category and alternative fuel of reference. The relevant LCA studies (identified in Martineau et al., (2010), a systematic review of the LCA literature on the use of alternative fuels in cement manufacturing), were analyzed and their findings merged with the others, along with any new LCA research. Martineau et al.'s search ended in January 2010; therefore, all relevant LCA studies published between the last months of 2009 and the execution of this second phase were added.

Including both LCA and non-LCA studies will enable the reader to explore the issues from two different points of view. The LCA studies provide a systemic assessment of the use of alternative fuels, considering all phases of a fuel's life cycle, and different end-of-life options; non-LCA studies explain the impact of using alternative fuels only in terms of cement kiln combustion.

With respect to non-LCA studies, only documents published from 1990 to 2010 were included in the literature search. This is due to the increasing interest in the topic over the last two decades and, hence, a greater number of published documents from that twenty-year period, the lack of a relevant number of documents published before 1990, and the possible technical obsolescence of such older reports.

One criterion taken into account during this phase was the generalizability of the findings. In fact, results that could only be obtained exclusively within a certain context were much less useful for the purposes of this study. For this reason, context-specific findings will be included in the next sections of this report to keep the information retrieved, but they are considered as neither positive nor negative.

1.4.3. Alternative Fuels Considered

As noted in Section 1.2, eight classes of alternative fuels were investigated, based on the types of alternative fuels currently in use or those that are suitable for use in cement kilns. Some classes are referred to as a single type of waste (e.g., used tires or sewage sludge), while other classes refer to several different types of alternative fuels. For instance, in IC&I residues, different types of waste (e.g., solvents and carpets) are included. However, the classification of fuel type was carried out considering the definitions used in the literature and also the implications deriving from the first phase of the project.

Particular mention should be made for the biomass class. Technically, most of the alternative fuels considered are biomass-based (e.g., animal and bone meal, biosolids, certain municipal solid wastes, wood waste, etc.). However, this class includes *all* the biomass fuel types not already included, such as rice husks and cottonseed oils.

A detailed description of the alternative fuels considered in this study can be found in Section 3.

1.5. Report Structure

Section 1 provided a general overview of the study, its background and context. Section 2 explains the literature retrieval process, methodology and results; Section 3 examines the main findings; Section 4 explains the methodology used to synthesize the findings, and also contains the tables with the synthetic representation of the findings and a discussion of the tables. Finally, Section 5 presents the conclusions of this study and explains the main implications for policymakers and other stakeholders.

2

state of the literature

This section presents the methodology used for the literature retrieval. Academic, institutional and practitioner databases were investigated in order to retrieve the best knowledge available about the topic. Due to the rapid development of technology in this field, only documents published from 1990 to 2010 have been included. Some gaps in the literature were highlighted during this phase and are noted in this report. More details about the methodology are available in Appendix 7.1.

2.1. Methodology used for literature retrieval

The document search was performed considering four categories of documents:

- Academic papers
- Institutional reports
- Practitioner reports
- Case studies

Search strings were created and used in the database search to answer questions RQ1 and RQ2 (see Table 7.1). The search strings for RQ1 used seven clusters of keywords (cement manufacturing, alternative fuels, fossil fuels, environmental impact, economic impact, health impact, and social impact), from which eight search strings were generated.

An ex-post refinement of the results was also performed to include only LCA studies published from 2009 in order to integrate the previous study (Martineau et al. 2010).

One search string was created for RQ2 and included the main end-of-life options for the alternative fuels considered. Keywords referring to the cement industry were combined with keyword related to energy and fuel issues and included to narrow the research to the truly relevant documents in order to compare the use of alternative fuels in cement production with the other end-of-life options.

2.2. Academic Papers

Using the search strings noted above, the search for academic papers was conducted in 10 academic databases.

Initially, 104 papers were considered relevant for RQ1. Following the refinement phase, 32 papers were judged relevant and were included in the literature analysis. All of these papers contain quantitative findings.

Similarly, for RQ2, 22 papers were initially retrieved from which 10 were considered relevant following a second refinement. From these searches, gaps in the literature emerged and these are discussed in Section 2.7.

2.3. Institutional Reports

Seventeen institutional databases were screened including those from consulting organizations, cement manufacturers' associations, international research institutes, and governmental organizations.

The search strings previously developed for the academic databases were used as a source for new search strings and then adapted to the different kinds of documents searched and to the search string limits of certain databases (see Table 7.2). Search strings differed depending on the institution. The search for documents published by cement-related institutions was not performed for RQ2 primarily because these institutions focused more on incineration in cement kilns than other end-of-life options for alternative fuels.

From these searches, 19 documents were judged potentially relevant for RQ1; 16 were judged potentially relevant for RQ2. Gaps in the literature also emerged in this case (*see Section 2.7*).

2.4. Practitioner Reports

The research for documents in practitioners' databases was performed only for RQ1 as it was assumed that information about other end-of-life options for alternative fuels was not available in practitioners' publications. Ten cement manufacturers were included in the search, providing 20 potentially relevant documents.

Publications that included case studies and sustainability reports were the most common among the documents retrieved. To maintain a high quality level of research, other document types (e.g., press releases and website pages) that were found during the search were not considered.

The majority of documents found were published between 2007 and 2009, which indicates an increasing interest in the topic in the last few years.

2.5. Case Studies

There were very few documents dealing with the use of alternative energy in the six case study databases screened and only stand-alone case studies were taken in consideration. Two documents were classified as potentially relevant for the research at the end of the screening. Readers should note that the search for case studies was limited to RQ1.

2.6. Other Documents

Additional documents suggested by the Guidance Committee[2] and the LCA studies reported in the previous phase (Martineau et al., 2010) were included in the literature assessment.

2.7. Gaps in the Literature Retrieval

Academic papers covering the social impact of the use of alternative energy sources in cement manufacturing were not identified. In addition, none of the institutional documents that were retrieved analyzed the social impact of using alternative fuels, and little information was found in practitioner reports, which indicates that a thorough knowledge of the topic is missing.

More details about the costs related to the use of alternative fuels in cement kilns are required; in fact, few findings about this topic emerged from the institutional reports.

Sustainability reports from practitioners provided detailed data about emissions. However, these reports averaged data based on all the cement plants belonging to a specific organization; as such, it is difficult to understand, in detail, the contribution made by alternative fuels to the reduction (or increase) of emissions.

Academic papers did not address comparisons between the use of animal and bone meal, IC&I residues, and waste wood in cement kilns with other end-of-life options. For the other alternative fuels considered, the documents retrieved made a comparison among a subset of the possible end-of-life options, highlighting another gap in the literature. For RQ2, academic papers did not discuss health or social impacts, and economic impacts were investigated for few end-of-life options. One document dealing with social impacts for RQ2 was found among the institutional reports retrieved, but this was deemed insufficient for a comprehensive knowledge of the topic.

2.8. Summary

Seventy-three documents were retrieved from the literature screening for RQ1 (32 academic papers, 19 institutional reports, 20 practitioner reports, and two case studies). In addition, the three LCA studies from found in Martineau et al. (2010) were included in this review. Although some gaps in the literature emerged, the number of documents retrieved was deemed sufficient.

[2] The NBS wishes to thank Professors Doug Hooton and Heather MacLean of the University of Toronto, as well as John Cuddihy of the Cement Association of Canada and Luc Robitaille of Holcim Cement for their guidance and feedback throughout this project. This report is the work of the authors and the NBS. Any errors, omissions or other weaknesses are our own and not a reflection of the Guidance Committee's diligent input. Moreover, the report's findings represent the authors' best interpretation of the body of literature and are not necessarily endorsed by the Committee members.

For RQ2, 26 documents were judged to be relevant (10 academic papers and 16 institutional reports). The search for documents related to RQ2 was not performed on practitioners' or case study databases. Some LCA studies from Phase 1 were considered consistent with RQ2 and were included.

The gaps in the literature that emerged during this phase indicate that the social impact of using alternative fuels in cement manufacturing needs to be investigated. Such an investigation could help make the practice more acceptable for certain stakeholders, such as local communities or environmental organizations. Comparable numerical data are also missing, which would be helpful in providing direct results to people interested in the topic. Finally, there is also a lack of documentation that compares the various end-of-life options with the combustion of waste in cement kilns.

3

findings

As described in Section 2, approximately 110 documents were retrieved (academic papers, institutional and practitioner reports, and case studies, as well as the LCA studies from Martineau et al., 2010) and analyzed to extract their main findings. Of these, only the most general findings for RQ1 and RQ2 are presented here and do not include any site-specific results that could bias the perception of the topic. The findings are divided among three different groups for each alternative fuel—environmental and human health impact, economic impact, and social impact—and cover the impact categories presented in Section 1. As in the literature retrieval phase, gaps also emerged during this analysis. These gaps are discussed at the end of this section and explain what is missing from the literature retrieved, as opposed to the gaps referred to in Section 2.7, which clarify what is missing in the overall literature.

3.1. Cement Production Using Alternative Fuel

In this section the findings for RQ1, extracted from the analysis of the literature, are merged and described for each alternative fuel class. Each finding matches an impact category. Eleven impact categories were considered and are grouped by their area of interest (see Section 1.4.1).

3.1.1. Municipal Solid Waste

Municipal solid waste (MSW) includes household waste, refuse derived fuels (RDF), solid recovered fuels (SRF), and waste derived fuels (WDF).

Environmental and Human Health Impact

The use of MSW implies a reduction of the use of fossil fuels in cement kilns (Heidelberg, 2007b; Heidelberg, 2007d; Hashimoto et al., 2010). Consequently, many studies verify a net reduction in CO_2 emissions in comparison to fossil fuel combustion (UK Environment Agency, 2008; Heidelberg, 2007b; Heidelberg, 2007d; Hashimoto et al., 2010; Heidelberg, 2007a; U.S. Environmental Protection Agency, 2008; Genon and Brizio, 2008). One study (U.S. Environmental Protection Agency, 2008) also found that the use of MSW in cement kilns reduces methane emissions, the rationale being that using MSW as an alternative fuel avoids landfilling waste, a source of methane emissions (methane is approximately 20 times more effective at trapping heat in the atmosphere than carbon dioxide).

In general, air pollutants are reduced when MSW is used as a fuel in cement kilns instead of fossil fuels, and reductions in NO_x and SO_2 emissions are also cited in many studies.

Genon and Brizio (2008), for example, state that emissions depend partly on the composition of the fuel. That study analyzed RDF composition, in particular nitrogen, sulphur, and chlorine content, and affirmed that the formation of nitrogen oxides is related to the temperature of the kiln, the residence times, the types of burners, and the amount of nitrogen in the fuel. Hence, nitrogen content is linked to the formation of NO_x and the study showed that the content of nitrogen in RDF is lower than in fossil fuels (0.3-0.5% versus 1.5-2%), meaning that NO_x emissions from RDF are lower than for fossil fuels, all other things being equal.

The Genon and Brizio study found a similar situation in terms of sulphur content (0.1-0.2% for RDF versus 3-5% for fossil fuels), and the authors concluded that problems regarding precipitation and clogging could be excluded. The opposite, however, was found for chlorine (0.3-0.5% for RDF versus 0.1% in coke), which implies that the use of RDF can create problems, such as the volatilization of chlorides. Therefore, the composition of the fuel used in kilns, can influence the pollutant emissions.

Two other studies described a reduction of CO emissions (Mokrzycki et al., 2003; Cheung et al., 2006) and one report showed a reduction in particulate emissions (UK Environment Agency, 2008).

With the exception of one study (Sarofim et al. 1994), many studies found that dioxin and furan emissions decrease when MSW is used as a fuel. Dioxins and furans comprise a family of organic compounds which have the potential to be created and emitted during the cement production process. Seventeen of these compounds are of particular concern, but at the moment, the formation of dioxins and furans is still not completely understood. As stated in Karstensen (2006), dioxins and furans can result from "a combination of formation mechanisms, depending on kiln and process design, combustion conditions, feed characteristics, and type and operation of air pollution control device equipment." In other words, compounds in the fuel can affect the formation of dioxins and furans.

The Sarofim study analyzed actual plant data from six kilns, three of which burned liquid waste and three that burned a combination of liquid and solid waste. The study authors noticed that there was no particular trend for dioxin and furan emissions when waste derived fuels were substituted for fossil fuels; based on their data, it is the completeness of combustion that influences dioxin and furan emissions. They also noted that neither the type of kiln nor the form of the waste derived fuel (solid or liquid) influences dioxin and furan emissions. The authors concluded that special attention must be paid to solid waste derived fuel because of its less efficient burnout of hydrocarbons, pollutants that do not seem to affect the formation of dioxins and furans.

The situation is similar for hydrogen chloride (HCl) emissions. Mokrzycki et al. (2003) showed the difference in HCl emissions when using two different kinds of fuels derived from MSW: PASr and PASi. According to the authors, PASr is a fuel obtained from "paper, cardboard, foil, cloth, textile, plastic containers, tapes, cables, and cleaning agents" that may be contaminated by oil, fat, lubricants, and paint; PASr is a fuel obtained when a sorbent (sawdust or tobacco dust) is mixed with waste from "paint, varnish, heavy post distillation fractions, and diatomaceous earth contaminated with petroleum-based waste." They tested both fuels in a Polish cement manufacturing plant and found that emissions varied. For instance, HCl emissions increased when PASi was applied (from 0.4109 kg/h without PASi to 0.9948 kg/h with PASi), and decreased when PASr was applied (from

3.48% of emissions to air without PASr to 0.993% with PASr). This study, therefore, shows that the quality of the fuel used can strongly affect the environmental performance of a plant.

Metal emissions show different results. Metals can be introduced into kilns through fuels. Most are locked into the clinker, while metals that are partly or completely volatile are not. Among this latter class, metals such as mercury, thallium, and cadmium, are an issue. To avoid metal emissions to the atmosphere, kilns are equipped with filters that capture the volatile compounds. However, stack emissions can occur if the filters are not managed correctly (Karstensen, 2006). In general, an increase in mercury emissions has been demonstrated (UK Environment Agency, 2005c; Genon and Brizio, 2008; Sarofim et al., 1994).

A UK Environment Agency report (2005c) that dealt with substitute liquid fuels (SLF, produced when organic wastes are blended) cited trials conducted at a UK cement plant. The trials were performed by comparing a baseline of coal and petroleum coke mixed with 20% SLF. For the baseline case, mercury emissions were reported equal to 0.0011 mg/Nm^3; in the actual trials with SLF the emissions were equal to 0.0027 mg/Nm^3. In both cases, the values are below the European Union (EU) limit of 0.05 mg/Nm^3.

The Genon and Brizio study carried out a simulation based on real data and provided maximum and minimum mercury emissions for four different scenarios. When using 100% petroleum coke, emissions ranged between 0.00029 mg/Nm^3 and 0.00143 mg/Nm^3. A significant increase was verified when 50% of the petroleum coke was substituted with RDF; in this case, emissions ranged between 0.00127 mg/Nm^3 and 0.00524 mg/Nm^3, still well below the EU limit. The situation was slightly different when 100% coal was combusted. In that case, emissions ranged between 0.00034 mg/Nm^3 and 0.07588 mg/Nm^3 (beyond the EU limit). When 50% coal was combined with 50% RDF, emissions ranged between 0.00130 mg/Nm^3 and 0.04246 mg/Nm^3. The Sarofim study, referred to above, found an increase in mercury emissions when MSW was mixed with coal and tires, but they cautioned that the data on mercury were “highly variable and prone to uncertainty.”

Another UK Environment Agency report (2008) found that if the MSW was chloride rich, it could generate a dust disposal problem, which would affect clinker quality, even though most of the ashes are incorporated within the clinker (Heidelberg, 2007d). In summary, the total impact of emissions to air was reduced relative to fossil fuel combustion (UK Environment Agency, 2008; U.S. Environmental Protection Agency, 2008).

Many studies concluded that using MSW reduces the quantity of waste going to landfill.

Economic Impact

The cost of MSW (by unit weight) is lower than fossil fuels (UK Environment Agency, 2008; Genon and Brizio, 2008). However, due to the lower energy content in MSW, the cost per heat unit can be higher than fossil fuels as for RDF compared with coal (Genon and Brizio, 2008). It should be highlighted that the use of MSW also implies a reduction of the energy costs for coal grinding (UK Environment Agency, 2008; Heidelberg, 2007d). This is valid for all the alternative fuels considered, although some exceptions are pointed out in later sections.

The Genon and Brizio study also noted the advantage of territorial distribution of MSW, which can increase the availability of the fuel.

Other Social Impact

Studies that deal with the social impact of using MSW in cement kilns were not retrieved. This gap in the available knowledge must be filled in order to provide a complete understanding of the topic.

3.1.2. Industrial, Commercial and Institutional Residues (IC&I)

For this category, IC&I residues have been grouped (e.g., automobile shredder residue and scrap carpets).

Environmental and Human Health Impact

IC&I residues can be used as both alternative raw materials (U.S. Environmental Protection Agency, 2008) and alternative fuels in cement manufacturing, reducing the energy required from fossil fuels when using residue streams such as spent solvents (Seyler et al., 2005). CO_2 emissions are influenced by the particular type of waste; for instance, due to higher volatile carbon content, carpet waste increases CO_2 emissions compared to coal (Konopa et al., 2008); however, solvents, filter cake, paint sludge, and fluff result in a decrease (Devos et al., 2007).

Some studies show a reduction of nitrogen oxides when using IC&I residues compared to fossil fuels (UK Environment Agency, 2008; Giannopoulos et al., 2007; Seyler et al., 2005). The exception is scrap carpet (U.S. Environmental Protection Agency, 2008; Lemieux et al., 2004; Konopa et al., 2008). The Lemieux study showed that the increase of nitrogen oxides, when scrap carpets are combusted in cement kilns, could be attributed to the preparation and feeding process. According to the study results, the authors reported that nitrogen oxide emission rates are highest when low carpet feed rates, high kiln temperature, and high feeder-to-burner air ratios are verified. The U.S. Environmental Protection Agency report (2008) and the Konopa study, mentioned above, found that one of the causes for this increase was due to the nylon content in certain kinds of carpet (nylon carpets contain 4-5% nitrogen by mass, while coal contains 1%).

The documents retrieved agreed that using IC&I residues reduces SO_2 emissions compared to the emissions from using fossil fuels (UK Environment Agency, 2005c; UK Environment Agency, 2008; Mlakar et al., 2010; Konopa et al., 2008).

The literature is inconclusive with respect to potential changes in CO emissions resulting from the use of alternative fuels. It should be noticed that while CO can be deadly in close environments such as a house, ground level CO emissions from tall stacks, such as kiln and clinker cooler stacks are not a concern for human health from a direct exposure perspective, nor is CO an appropriate indicator of the quality of combustion in a kiln; rather, the concern with CO emissions is related to its status as an ozone (and smog) precursor.

The UK Environment Agency (2008) report found that particulate emissions do not change as a function of the fuel used in cement manufacturing.

Two studies included information about dioxin and furan emissions and found that no change was demonstrated (UK Environment Agency, 2005c; UK Environment Agency, 2008). Emissions from volatile organic compounds present small reductions. Trials conducted at a British cement plant using 20% SLF and 80% coal and petroleum coke showed a small reduction (~3.5%) in volatile organic compounds (UK Environment Agency 2005c).

With respect to metals, the UK Environment Agency (2005c; 2008) confirmed that there is no statistically significant emission change in comparison to fossil fuel combustion; however, the Mlakar study showed a reduction in mercury emissions and the Seyler study showed a reduction in heavy metal emissions when waste solvents were used. The Mlakar study linked the reduction in mercury emissions to the relative content of mercury in waste oil and petroleum coke. In eight samples of petroleum coke, the study authors found 214 ng/g of mercury and 14.9 ng/g of mercury from two samples of waste oil. Using models, the Seyler study performed a life cycle assessment on the use of waste solvents from which a reduction in mercury emissions emerged. These latter two documents do not specify whether the reduction of mercury emissions was statistically significant.

Ashes from combustion are incorporated within the clinker, which reduces the amount of raw materials required, particularly calcium carbonate. Calcium carbonate is not only present in cement as limestone but is also used as filler in carpet backings and in clinker production; therefore, if carpet is used as a fuel, it reduces the need for additional calcium carbonate to be added to the kiln (Lemieux et al., 2004).

To conclude this section, Devos et al. (2007) declared that some IC&I residues such as solvents, filter cake, paint sludge, and fluff, have a favourable environmental impact.

Economic Impact

According to the UK Environment Agency (2005c), although the economic impact of using solvents in cement kilns is site specific, their use can cause output reductions. Studies about other IC&I residues could not be found.

Using IC&I residues in cement kilns requires pre-treatment (LaFarge, 2003; U.S. Environmental Agency, 2008; Boughton, 2007), and any technological kiln upgrades would depend on the type of waste to be used.

The availability of fuel depends on the type of waste. Automobile shredder residues and scrap carpet, for example, are readily available (U.S. Environmental Agency, 2008; Boughton, 2007), but there is no guaranteed supply of clarified slurry oil sediments (U.S. Environmental Agency, 2008).

For a full accounting of the economic impact of the use of IC&I residues, more studies are required.

Other Social Impact

As with the discussion of MSW, information about the social impact of burning IC&I residues in cement kilns is missing. The scientific community needs to fill this knowledge gap.

3.1.3. Plastics

Very few studies analyzed the effect of using plastic waste as an alternative fuel in cement kilns.

Environmental and Human Health Impact

One of the few findings extracted from the literature showed a reduction in landfill GHG emissions when plastics were used in the combustion process for cement manufacturing (U.S. Environmental Agency, 2008).

The chlorine content of plastics can be the cause of HCl emissions (Heidelberg, 2007b). Under specific conditions, chlorine can influence the formation of precursors of dioxins and furans (Karstensen, 2006) contributing to the increase of dioxin and furan emissions (U.S. Environmental Agency, 2008). Hence, practitioners should be very careful when selecting the kind of plastics to be burned in kilns.

As a waste management option, burning plastics in cement kilns avoids disposal problems (Heidelberg, 2007b; U.S. Environmental Agency, 2008).

The lack of findings in this field limited a full assessment of the impacts of burning plastics.

Economic Impact

Plastics have an energy content comparable to coal (UK Environment Agency, 2001; U.S. Environmental Agency, 2008). In contrast to other kinds of waste, and due to the competition with other end-of-life options such as recycling, plastics need to be purchased by the practitioner (UK Environment Agency, 2001).

Burning plastics could require a system to extract chlorine particulates; such a system has low capital and maintenance costs (LaFarge, 2003). The quality of the material collected is also an issue because the chlorine content can be detrimental to industrial operations (LaFarge, 2003; U.S. Environmental Agency, 2008).

The availability of plastics raises some issues. First, there is competition with other end-of-life options and as a consequence it is difficult to achieve consistent quantities of materials. Second, the waste stream must be separated to ensure a sufficient quality of the alternative fuel in terms of chlorine content (U.S. Environmental Agency, 2008), in order to reduce HCl emissions and avoid the requirements of waste sorting or systems to extract chlorine.

Other Social Impact

Information about the social impact of plastics was not found in the available literature. The topic, therefore, needs to be investigated.

3.1.4. Sewage Sludge and Biosolids

This category includes sewage sludge, biosolids and wastewater sludge from production processes.

Environmental and Human Health Impact

According to a Heidelberg case study (2011), the disposal of sewage sludge at the Guangzhou cement plant preserves coal and limestone consumption.

Many of the studies reviewed considered CO_2 emissions as climate neutral, unlike fossil fuels.

With respect to burning sewage sludge in cement kilns, little information could be found on critical air contaminants (CACs). Nitrogen oxide emissions are lower than when fossil fuels are burned (U.S. Environmental Protection Agency, 2008), but the reverse is true in terms of sulphur dioxide emissions (probably due to the different sulphur content of coal). One study showed an increase in sulphur dioxide emissions (Cartmell et al., 2006), but more studies are needed to increase the reliability of these findings.

Hazardous air pollutant (HAP) emissions data are not available in the literature, representing a gap. Findings about metal emissions are uncertain. The Cartmell study stated that sewage sludge causes an increase in heavy metal emissions compared to fossil fuels, but Conesa et al. (2008) argued with this finding, saying that there was no correlation between fuel and metal emissions. However, the Heidelberg case study (2011) states that at least a portion of heavy metals is incorporated into the clinker and the mineral components are fit for it.

Devos et al. (2007) asserted a favourable environmental impact when sewage sludge is combusted in cement kilns.

One study looked at the risk of cancer from exposure to heavy metal and dioxin and furan emissions (Schuhmacher et al., 2009). The Schuhmacher study was based on a Spanish cement plant that uses a fuel composed of 80% petroleum coke and 20% sewage sludge. They estimated the direct exposure to pollutants by considering air inhalation, dermal absorption of soil and dust, and ingestion of soil and dust. The use of sewage sludge as an alternative fuel made the cancer risk from heavy metal emissions exposure decrease by 4.60 cancers per year per one million adults, while the cancer risk from exposure to dioxins and furans increased by 0.04 cancers per year per one million adults, a net decrease of 4.56 cancers per year per one million adults.

Economic Impact

Nadal et al. (2009) and Cartmell et al. (2006) found an increased economic return when using sewage sludge instead of fossil fuels, even though sewage sludge has a lower energy content than coal (U.S. Environmental Protection Agency, 2008) and special silos are required to store the sludge and avoid contamination (UK Environment Agency, 2001).

The handling and storage of sludge may be difficult. Dehumidification to avoid self-heating (Environmental Agency, 2008) and drying are required, as well as additional pollution control (U.S. Environmental Protection Agency, 2008). Reducing the significant water content of sewage sludge could be very costly. The pathogen content of sludge is another storage issue that must be considered by practitioners (U.S. Environmental Protection Agency, 2008).

Sewage sludge combustion is considered a sustainable disposal method (LaFarge, 2007a; U.S. Environmental Protection Agency, 2008), primarily because combustion destroys the pathogens held in the sludge. However, sewage sludge introduced into a plant must contain a level of pathogenic organisms lower than the limit fixed by regulations (U.S. Environmental Protection Agency, 2008) in order to reduce the health risks to employees during the handling stage.

Sewage sludge is largely available as fuel for cement manufacturing (U.S. Environmental Protection Agency, 2008).

Other Social Impact

Some findings about the social impacts of using sewage sludge as an alternative fuel were found in the literature. For example, sewage sludge does not compete with nutrition of humans and animals, unlike some biomass such as palm kernels and rice husks, which are used to feed animals. Nonetheless, burning sewage sludge can create public perception issues (U.S. Environmental Protection Agency, 2008).

3.1.5. Animal and Bone Meal

Animal and bone meal is a by-product of the rendering and food industries. Animal meal obtained from contaminated carcasses (e.g., bovine spongiform encephalopathy, or BSE) is included in this category.

Environmental and Human Health Impact

As in other cases, the use of animal and bone meal as fuel implies a reduction in the use of fossil fuels in cement kilns (Heidelberg, 2007c; LaFarge, 2003; Chaala and Roy, 2003). CO_2 emissions from burning animal and bone meal are also lower than the emissions from fossil fuel combustion (Heidelberg, 2007c; LaFarge, 2003; Heidelberg, 2008) and are deemed climate neutral (European Cement Association, 2009; Heidelberg, 2009; Heidelberg, 2007a; LaFarge, 2007a).

Few considerations are made with respect to air pollutants. Chaala and Roy (2003) found that nitrogen oxides could be converted into neutral molecular nitrogen by the minerals in cement. Abad et al. (2004) found that animal and bone meal combustion has no impact on dioxin and furan emissions. More study is required in this area as these two studies were the only ones found in the available literature.

Animal and bone meal combustion produces tallow as a by-product that can be sold for soap manufacturing. The material received from abattoirs is heated to 130°C to sterilize it and to split the liquid fat fraction, namely tallow, for further processing. The remainder is then pressed to increase the tallow yield and then ground to produce fuel (Heidelberg 2007c). Studies showed no changes in emissions to air, land or water (Heidelberg, 2007c; LaFarge, 2003).

Burning animal and bone meal in cement kilns is a safe and environmentally sound way to destroy contaminated animals (e.g., BSE-contaminated animals) (World Business Council for Sustainable Development, 2005; European Cement Association, 2009; LaFarge, 2008). Moreover, it reduces the demand for landfills and their associated environmental and health risks (Heidelberg, 2007c; Heidelberg, 2008).

Finally, a Heidelberg report (2008) stated that the combustion of animal and bone meal in cement kilns has no detrimental impact to human health. In fact, the composition of meat and bone meal allows the fuel to be completely consumed in the kiln.

Economic Impact

Animal and bone meal is considered 100% carbon neutral by the EU's carbon cap and trade system (Heidelberg, 2007a; Heidelberg, 2009). If a similar system were created in Canada, animal and bone meal could generate emission advantages for practitioners.

Animal and bone meal fuel does not impact on cement quality (Chaala and Roy, 2003), even though bone meal contains phosphorous which, in large quantities, can be detrimental to the clinker. An important issue is the cleaning and disinfection of storage areas to avoid contamination (UK Environment Agency, 2001).

Due to the unreliable availability of animal and bone meal this can be an operational hazard, triggering unexpected plant shutdowns (Italcementi, 2009).

Other Social Impact

Studies on the social impact of burning animal and bone meal in cement kilns are missing.

3.1.6. Waste Wood

The waste wood category includes scrap wood, sawdust, and paper residues from industrial processes.

Environmental and Human Health Impact

As in the previous cases, the use of waste wood in cement kilns reduces the amount of fossil fuel required by industry (Walker et al., 2009). The ashes resulting from the combustion of waste wood are mixed with raw material in the clinker, thus reducing the requirements for new input materials (Heidelberg, 2007e).

Many documents described the use of waste wood as a viable way to reduce CO_2 emissions due to its climate neutrality.

The metals content of waste wood can be a problem if not limited at the source (UK Environment Agency, 2001).

A Heidelberg report (2007e) shows that using, storing, and handling waste wood does not produce additional waste and that the ash from the combustion of the wood is fully incorporated into the clinker. No changes were reported with respect to releases to air, water or land with the exception of an effective reduction in GHG emissions due to the carbon neutrality of biomass (Heidelberg, 2007e).

The use of waste wood in cement kilns reduces the demand on landfills (Heidelberg, 2007e; U.S. Environmental Protection Agency, 2008).

In general, the practice of combusting waste wood in cement kilns has a favourable environmental impact (Devos et al., 2007).

With respect to the cancer risk, the above quoted Heidelberg report (2007e) declared that the cancer risk was unchanged when compared to burning fossil fuels.

Economic Impact

In comparison to fossil fuels, the use of paper residues can be economically disadvantageous due to its lower energy content (UK Environment Agency, 2001; U.S. Environmental Protection Agency, 2008). Suppliers of paper residues should be paid (UK Environment Agency, 2001), as there could be competition with other end-of-life options, such as recycling. However, savings arise from the reduction of energy used for operations, such as coal grinding (Heidelberg, 2007e), and if incentives are given for per unit CO_2 reductions (Walker et al., 2009).

Additional equipment (e.g., equipment to keep sawdust dry to reduce fire hazard) may be required (U.S. Environmental Protection Agency, 2008).

The availability of waste wood is high but the competition with other end-of-life options can make the supply uncertain and costly (U.S. Environmental Protection Agency, 2008; Walker et al., 2009). A Heidelberg report (2007e) suggested making the system flexible so that if waste wood is unavailable, cement manufacturers can switch to other fuels.

Other Social Impact

No impact on communities was reported in literature, other than the above cited health impact.

3.1.7. Used Tires

The practice of substituting fossil fuels with scrap tires is widespread in the cement industry; hence, there is a relative abundance of documents that deal with the issue.

Environmental and Human Health Impact

The use of scrap tires in cement kilns reduces resource consumption. In fact, scrap tires often replace fossil fuels such as coal (LaFarge, 2003) and, therefore, the amount of raw materials required by industry (UK Environment Agency, 2001; U.S. Environmental Protection Agency, 2008). Since passenger car tires are composed of 18.3% biomass fraction and truck tires are composed of 29.1% biomass fraction (Clauzade, 2009) the effect of reducing net CO_2 emissions in comparison to fossil fuels is well documented (European Cement Association, 2009; International Energy Agency, 2009; Portland Cement Association, 2008; Cook and Kemm, 2004).

Differing results exist for SO_2 and NO_x emissions, suggesting that the issues are case specific. Prisciandaro et al. (2003) analyzed the emissions from an Italian cement plant using petroleum coke and less than 20% tires. Through statistical analysis, the study asserted that, as compared with using 100% petroleum coke, the combustion of tires with petroleum coke in cement kilns increases SO_2 and NO_x emissions. The study found that the increase of NO_x emissions could be linked to the burning conditions of the kiln, and in particular to excess air. Increased emissions of SO_2 are supposedly caused by the incomplete combustion of tires, even though the amount of sulphur in the mix of petroleum coke and tires is lower than for petroleum coke alone.

Carrasco et al. (2002) studied a Canadian cement factory that used coal as well as a combination of coal and scrap tires. That study found a decrease in NO_x emissions but an increase in SO_2 and particulate emissions. They did not cite the percentage of scrap tires used as fuel; however, they mentioned that the combustion efficiency was one of the main causes of pollutant emissions.

The UK Environment Agency (2008) conducted a study on a cement manufacturing plant in Dunbar (using 25% tires), which showed an impact reduction, calculated through an environmental quotient, for NO_x. For SO_2 and particulate emissions, the situation was uncertain and case specific, as findings showed both increases and decreases. The report suggested that this was due to the pyritic sulphur content of raw materials, which has a substantial influence on emissions. The report also cited the same behaviour in four other UK cement factories.

A U.S. Environmental Protection Agency report (2006b) stated that NO_x emissions depend mainly on the combustion process, while SO_2 emissions depend on the sulphur content of the fuel. The report found that although the use of tire derived fuel did not decrease NO_x emissions it did not provide further explanation about the methodology of the research. Another U.S. Environmental Protection Agency report (2008), however, found that the use of scrap tires in cement kilns decreases NO_x emissions.

An International Energy Agency report (2009) stated that burning tire derived fuel in cement kilns, instead of fossil fuels, decreased both NO_x and SO_2 emissions but the report did not provide additional insights into this finding.

A LaFarge document (2003) contained a case study about the use of scrap tires in cement kilns. In that case, a cement plant in Atlanta that used 20% scrap tires as fuel decreased NO_x emissions by 4.6%.

Finally, two Portland Cement Association reports (2008, 2009) found that nitrogen oxide, sulphur oxide, and particulate emissions were lower when scrap tires substituted a portion of the fossil fuels. They also found no statistically significant differences in those emissions.

Similarly, the literature revealed differing results in terms of metal and dioxin and furan emissions. Conesa et al. (2008) showed that dioxin and furan emissions increased when year-long tests were performed at a real plant. By contrast, the Carrasco study, mentioned above, found that using scrap tires in cement kilns reduced the amount of dioxins and furans emitted. The Portland Cement Association studies collected data from 31 cement plants that used tire derived fuel and found statistically significant decreases in the emissions of dioxins and furans. However, the Prisciandaro study, cited above, showed that the emissions of dioxins and furans was similar (and well below the limit) for cement kilns fed with 100% petroleum coke and for kilns fed with 80% petroleum coke and 20% scrap tires. Abad et al. (2004) studied three Spanish cement plants and found no statistical differences between the data obtained from plants that used conventional fuels or those that used a combination of fossil fuels and used tires (in a percentage of 9.4% in energy provided). This is similar to the findings of the UK Environment Agency report (2008).

Carrasco et al. (2002) found that, in comparison to fossil fuels, burning used tires in cement kilns increased HCl emissions.

There was wide acceptance among the available literature that using used tires as fuel in cement manufacturing reduces the need for additional new raw materials (tires contain iron and, if recovered, could reduce the need for iron mining and/or sourcing of alternative iron sources) (UK Environment Agency, 2008; International Energy Agency, 2009; Portland Cement Association, 2008; U.S. Environmental Protection Agency, 2008).

The same wide acceptance is found in terms of the reduction of air emissions when compared to fossil fuel combustion (UK Environment Agency, 2008; Portland Cement Association, 2008; Portland Cement Association, 2009; LaFarge, 2003; LaFarge, 2008).

The use of scrap tires in cement kilns is an environmentally sound end-of-life management option. It avoids eyesores and uncontrolled burning (Portland Cement Association, 2008), reduces landfill demand (Portland Cement Association, 2009; Heidelberg, 2007b; LaFarge, 2008; LaFarge, 2003; U.S. Environmental Protection Agency, 2008), and reduces the presence of mosquitoes (LaFarge, 2008), which can carry certain diseases.

Although burning scrap tires does not have negative health impacts, there are issues with public perception (U.S. Environmental Protection Agency, 2008; Cook and Kemm, 2004).

Economic Impact

Scrap tires have a higher energy content than coal (UK Environment Agency, 2005c; International Energy Agency, 2008; Portland Cement Association, 2008; Portland Cement

Association, 2009; U.S. Environmental Protection Agency, 2008) and their use as fuel makes plants more competitive due to the savings on coal (LaFarge, 2003).

Not all kilns are suitable to process whole tires, and the use of shredded tires increases fuel costs (U.S. Environmental Protection Agency, 2008). Moreover, additional pre-processing equipment may be required (UK Environment Agency, 2001).

The availability of scrap tires is generally good, despite the increasing competition for them with other end-of-life options (U.S. Environmental Protection Agency, 2008). However, this is not the case in Canada (particularly in Quebec), where the availability of scrap tires for cement manufacturing is becoming limited.

Other Social Impact

Other than the documents already referenced, no additional documentation could be found that dealt with other social issues.

3.1.8. Biomass

This category includes all biomass types not included in other categories, such as rice and coffee bean husks, palm kernels, algae, and cottonseed oils.

Environmental and Human Health Impact

The climate neutrality of CO_2 emissions from biomass combustion is broadly accepted in the literature; the use of biomass is also seen as an effective way to reduce greenhouse gases (International Energy Agency, 2009; Holcim, 2007; LaFarge, 2003) and fossil fuel requirements (Heidelberg, 2007b; Holcim, 2007; LaFarge, 2003; LaFarge, 2009a; LaFarge, 2009b). In addition, due to its readily available supply, when local biomass is used, transportation impacts are also reduced (LaFarge, 2003).

According to Royo et al. (2007), using biomass implies low SO_2 emissions, low dioxin and furan emissions, and very low heavy metal emissions.

Economic Impact

Typically, certain kinds of biomass (namely waste from industrial or agricultural processes) are less costly than fossil fuels, and therefore reduce fuel costs (LaFarge, 2009b). Using scrap biomass also helps to “close the loop,” by using the waste from one industrial process as input for another (Holcim, 2007; LaFarge, 2003).

Additional equipment may, however, be required to process biomass (LaFarge, 2003), which could result in higher operational costs.

Some Italcementi plants using biomass reported unscheduled shutdown and reduction in the availability of biomass (Italcementi, 2009), although the causes of these events are not clearly detailed. The U.S. Environmental Protection Agency (2008) noted that several cement plants no longer use agricultural by-products as fuel because of supply issues.

Other economic benefits include increasing the value of low-yield or nutrient poor fields (Uniland, 2004).

Other Social Impact

Due to the increase in demand, some studies found that the use of biomass in cement kilns can be a source of income for local communities (Holcim, 2007; LaFarge, 2008; LaFarge, 2009a; LaFarge, 2009b).

3.1.9. Hazardous Waste

Hazardous waste can be used as an alternative fuel in cement kilns, which also realizes the complete destruction of such waste.

Environmental and Human Health Impact

The combustion of hazardous waste in cement kilns reduces the fossil fuel requirements of plants (Cimpor, 2008; Heidelberg, 2007b; Lamb et al., 2004) and also reduces CO_2 emissions (Cimpor, 2008; Heidelberg, 2007b).

Heavy metal emissions vary with the specific element (Kleppinger, 1993; Denis et al., 2000). Chlorinated organic compound emissions, for example, are expected to decrease compared to the use of fossil fuels (Lamb et al., 1994). In general, dioxin and furan emissions do not vary (van Loo, 2008; Karstensen, 2008), although Lamb et al. (1994) asserted that such emissions do increase when liquid hazardous waste is used.

The Holcim report (2006) found that co-processing hazardous waste in cement kilns can be part of the solution for final treatment.

Economic Impact

The use of hazardous waste does not involve changes to manufacturing processes nor does it affect manufacturing quality (Cimpor, 2008). It is, therefore, suitable for any cement plant. Nevertheless, quick cooling in air pollution control devices can reduce dioxin and furan emissions (van Loo, 2008: Karstensen, 2008).

One drawback is the slow but steady decline of hazardous waste availability for cement kilns (U.S. Environmental Protection Agency, 2008).

Other Social Impact

There were no studies available regarding the social impact of hazardous waste co-processing in cement kilns.

3.2. Waste Management with Energy Recovery in Cement Kilns

This section presents the findings for RQ2. The impact categories are a subgroup of the ones used in Section 3.1 together with two more categories, namely eutrophication potential and technical/market feasibility (*see Section 1.4.1*).

Each impact category was evaluated for different end-of-life management options. It was not possible to include a general list of these options because they differ depending on the fuel type. However, the most recurrent options include:

- Reuse
- Recycle
- Energy recovery in cement manufacturing
- Incineration
- Incineration with electricity and/or heat generation
- Landfill

Comparisons between end-of-life management options were available for only some of the alternative fuel categories. The findings of studies that compared end-of-life options were prioritized; studies that did not compare end-of-life options were also considered, but only when they clearly contributed to RQ2. In a second evaluation step, the studies that did not allow comparisons between end-of-life options were considered neutral with respect to the analysis. More details on this point are available in Section 4.

3.2.1. Municipal Solid Waste

The types of waste included in this category are the same described in Section 3.1.1.
In addition to the ones previously cited, the end-of-life options considered are: production of densified RDF in pellet form, cogeneration in a coal-fired power plant, and a biomass combustion system using woodchips.

Environmental and Human Health Impact

Energy recovery is one way to increase the availability of heat and electricity generation without increasing fossil fuel use (U.S. Environmental Protection Agency, 2002a). Energy recovery of MSW in cement manufacturing limits heat and electricity generation through the combustion of waste in incinerators and through cogeneration in coal-fired power plants (Garg et al., 2009). Moreover, energy recovery in cement kilns requires higher electricity consumption than other end-of-life alternatives due to the composting process, which is necessary to make the fuel suitable for cement kilns (Morimoto et al., 2005; Morimoto et al., 2006). With recycling, it is possible to supply raw materials to industries (U.S. Environmental Protection Agency, 2002a); with composting, organic material rich in nutrients can be returned to the land (U.S. Environmental Protection Agency, 2002a). Recycling and combustion in cement kilns are not mutually exclusive; in fact, cement manufacturers often choose to burn only the post-recycled residues of MSW.

Landfilling appears to be the worst solution in terms of global warming due to the emission of methane and carbon dioxide (European Union, 1999). Incineration, with or without electricity or heat generation, lowers GHG emissions compared to landfilling or recycling and composting (European Environmental Agency, 2008). However, energy recovery in cement manufacturing offers better results than incineration (Fehrenbach, 2007; Morimoto et al., 2005; Morimoto et al., 2006) and results in an end-of-life option with the lowest global warming impact. This option is followed by cogeneration in coal-fired power plants (Garg et al., 2009).

The Garg study showed a potential SO_x emissions increase for MSW cogeneration in coal-fired power plants and biomass combustion; a slight increase of potential for co-processing in cement plants; and a decrease of potential for incineration with electricity and heat generation. Data on SO_2 emissions were available for few options, showing that incineration with heat generation can increase emissions, while incineration with heat and electricity generation and cogeneration in coal-fired power plants can decrease them; further reductions are possible with energy recovery in cement manufacturing (Garg et al., 2009).

Landfilling, as well as incineration, produces toxins and heavy metals that can leach into the water supply and soil (European Union, 1999). With energy recovery in cement manufacturing, these substances are partially transferred to the clinker (Genon and Brizio, 2006).

Incineration and composting MSW can push toxic substances into the food chain (European Union, 1999). With energy recovery in cement manufacturing, there is a slight increase of ashes with respect to combustion in coal-fired power plants, biomass combustors, and MSW incinerators (Garg et al., 2009), but in the cement kiln option ashes are taken up into the clinker (Haley, 1990). Ashes can also increase for cogeneration in coal-fired power plants and biomass combustion, but decrease with incineration with heat and electricity generation (Garg et al., 1990).

Incineration can spread hazardous substances onto water surfaces and landfilling can spread them on soil (European Union, 1999). Recycling and composting have the advantage of creating new jobs and a source of income for local communities while at the same time reducing the demand for landfills (U.S. Environmental Protection Agency, 2002a; U.S. Environmental Protection Agency, 2002b).

Economic Impact

Incineration costs are no greater than those for landfilling, but facility construction is expensive (Haley, 1990; U.S. Environmental Protection Agency, 2002a). Energy recovery in cement manufacturing offers cost reductions for waste treatment with respect to combustion in incinerators and landfilling of ashes (Morimoto et al., 2005; Morimoto et al., 2006).

Garg et al. (1990) analyzed the impact of energy recovery of RDF from MSW in four different UK-based scenarios: 1) a large-scale coal-fired power plant; 2) a MSW incinerator with the production of heat and electricity; 3) a biomass combustion system with the production of heat and electricity; and 4) a cement kiln where coal is substituted with 20% RDF by weight. The authors used a modelling framework for their analysis, which provided an energy and mass flow assessment, a risk analysis, an environmental assessment, and a financial assessment. From the overall assessment, combustion of RDF in cement kilns was the best option. Although it was the least preferred option from a financial perspective, the risks and emissions were the lowest. This type of combustion process is familiar to people who work in cement production as opposed to incineration facilities, which require qualified and trained technical staff for operation and maintenance (Haley, 1990).

The Haley study found that the composition of the fuel supplied was critical for cement plants to ensure a consistently high quality (similar to co-processing) and suggested that the minimum calorific value for using MSW for combustion, without supplementary fuel, should be about 5 MJ/kg. The study also confirmed that the combustion of RDF generated large amount of gases that could lead to production limitations. Another issue that must be addressed is the moisture level of MSW, which reduces the calorific value and can be detrimental to operations. In addition, the variability of fuel quality needs to be controlled. Pre-processing MSW could, in part, solve some of these issues, but would increase fuel costs.

3.2.2. Sewage and Wastewater Sludge

There are several end-of-life management options for sewage and wastewater sludge. In addition to the ones cited in Section 3.2, others include composting, anaerobic digestion, gasification, pyrolysis, and hydrothermal processes. Some less investigated end-of-life options were also considered, like the production of biofuels, the production of electricity in microbial fuel cells, cogeneration in coal-fired power plants, wet oxidation, use in cogeneration plants or in heat-only plants, and as a raw material in cement production.

Environmental and Human Health Impact

According to a European Environmental Agency report (1997), the agricultural use of sludge as fertilizer, composted or not, is the best disposal option in terms of resource consumption and conservation; energy recovery in cement manufacturing and incineration are the worst solutions. In fact, using nutrient-rich sludge can improve soil conditions (European Environmental Agency, 1997; U.S. Environmental Protection Agency, 1999a), although in some countries the direct application of sewage sludge as fertilizer is forbidden or limited. Murray et al. (2008) found that anaerobic digestion was the most preferable treatment option.

Burning sludge in cement kilns or in incinerators with energy recovery reduces the demand for fossil fuels due to the energy value of waste (European Environmental Agency, 1997). Other processes can generate products with an intrinsic value. For instance, pyrolysis produces pyrolytic gas and oil, which can be used as fuel or as an input for chemical industries (Fytili and Zabaniotou, 2008). Biogas is produced through anaerobic digestion and gasification (Fytili and Zabaniotou, 2008). Volatile fatty acids and organic compounds are the results of hydrothermal processes (Rulkens, 2008). Houillon and Jolliet (2005) state that incineration of sludge and the use of uncomposted sludge as fertilizer have lower non-renewable energy consumption rates.

In terms of global warming potential, landfilling emerges as the worst disposal method, while energy recovery in cement plants is considered the best one (Houillon and Jolliet, 2005).

Heavy metals in sludge can be an issue. Heavy metals can be released through agricultural use (if the sludge is not composted), energy recovery in cement kilns, and incineration

(Fytili and Zabaniotou, 2008). In some cases, notably energy recovery (European Environmental Agency, 1997) and incineration (U.S. Environmental Protection Agency, 1999a), metals can be locked in the clinker or in the ashes. However, gasification and pyrolysis can prevent many of the pollutant emissions associated with incineration (Fytili and Zabaniotou, 2008). In that study, the authors found that, during the pyrolysis process, the heavy metals in sludge were concentrated in a solid carbonaceous residue, a problem less crucial than in incineration. Comparing gasification and incineration, the authors reported that gasification is a net reductive process and can prevent problems such as “the need for supplementary fuel, emissions of sulphur oxides, nitrogen oxides, heavy metals and fly ash and the potential production of chlorinated dibenzodioxins and dibenzofurans.” In gasification, heavy metals are accumulated in the final residue, which can be a disposal challenge.

These end-of-life processes generate waste. For example, water resulting from wet oxidation needs to be disposed of (Fytili and Zabaniotou, 2008). However, waste from incineration can produce valuable by-products (U.S. Environmental Protection Agency, 1999a); ashes, for instance, can be used as an input for the production of building materials (Rulkens, 2008). On the other hand, residues from cement kiln combustion are included in the clinker, and thus do not represent a disposal issue (Murray et al., 2008).

Odour is a common concern when using sludge. Odours can be minimized when sludge is incinerated or co-processed in cement kilns (European Environmental Agency, 1997), but can be highly offensive if sludge is used as fertilizer (U.S. Environmental Protection Agency, 1999a). The application of sludge as non-composted fertilizer can also allow metals to enter into the human food chain (Fytili and Zabaniotou, 2008) and there is a lack of knowledge about the impact of pathogenic organisms and micro-pollutants on the human food chain (European Environmental Agency, 1997).

Economic Impact

Incineration and co-processing in cement kilns are considered capital-intensive disposal solutions; it should be noted however that, for co-processing, the capital equipment is already in place. Energy recovery in cement manufacturing also has the advantage of an existing infrastructure, other than the absence of cost variations for sludge handling (Murray et al., 2008). The use of sludge as fertilizer without composting is considered the cheapest option, despite the need for an investment in storage facilities (European Environmental Agency, 1997). Incineration with electricity generation requires a costly gas treatment system (Rulkens, 2008). Landfilling is also an expensive solution due to the likelihood of cost increases over time due to tipping fees, etc. (U.S. Environmental Protection Agency, 1999a). The treatment of gases in oxidation and pyrolysis is more complicated than in incineration, but the opposite is true for wet oxidation (Rulkens, 2008). The use of sludge in cogeneration plants is considered cost-competitive with respect to other combustion technologies under specific conditions (Horttanainen, 2010).

Incineration and co-processing in cement kilns are reputed to be technically reliable systems, showing a low sensitivity to sludge composition (European Environmental Agency, 1997). For gasification and pyrolysis, the process performance is much more complicated than for incineration and, for wet oxidation, a large-scale application is not yet available (Rulkens, 2008).

Other Social Impact

The use of sludge as fertilizer has a positive impact on plants and lands, speeding tree growth in forests and controlling soil erosion (U.S. Environmental Protection Agency, 1999a). Incineration, on the other hand, creates issues with communities because it is not the most acceptable disposal method for sludge (U.S. Environmental Protection Agency, 1999a). Other disposal options, such as anaerobic digestion that can create local jobs, are more favourable with communities (Sloan, 2009).

3.2.3. Plastics

The end-of-life management options for plastics are the same as those listed in Section 3.2, except for reuse, which was not considered in the documentation retrieved. Overall, the information available on the impact of disposal options is unsatisfactory. More studies are needed to fill this literature gap.

Environmental and Human Health Impact

Recycling and energy recovery in cement manufacturing reduces the net energy consumption compared to incineration (Krivtsov et al., 2004). Incineration, both with and without electricity production, results in the worst environmental performance among the other options (Jenseit et al., 2003). According to global warming indicators, incineration is the least favourable option (Shonfield, 2008). Landfilling is considered the worst option in terms of resource consumption and conservation, while recycling is the best, even though recycling is sensitive to the quality of the plastics used (Shonfield, 2008). It should be noted, however, that recycling plastics is less desirable if they must be transported over long distances (Lindhal and Winsnes, 2005).

Landfilling plastics presents the problem of non-degradability (European Environmental Agency, 1996). Incineration with electricity generation and co-processing in cement manufacturing produces the minimum amount of waste among the various options (Shonfield, 2008).

No air pollution data were available for comparison in the retrieved literature, which highlights the need for further research.

Economic Impact

Information about the economic impact of the considered options was not available. However, in terms of recycling, it is possible to use highly complicated waste streams without sorting needs (Deloitte, 2006).

3.2.4. Used Tires

Recycling used tires can be used to generate several products (e.g., artificial turf, asphalt road pavement, retention basin), each of which has environmental and economic impacts that must be separately analyzed. Other end-of-life management options commonly adopted, other than the ones cited in Section 3.2, are energy recovery in industrial boilers, pyrolysis, and use in civil engineering applications.

Environmental and Human Health Impact

Because scrap tires are a replacement for virgin rubber in some production processes, recycling and reuse are considered the least resource-consuming solutions (European Union, 2007). In spite of this, Corti and Lombardi (2004) stated that, from a resource consumption perspective, reuse has a worse environmental impact, compared to other alternatives, and indicated that energy recovery in cement kilns was the most favourable option. That study also considered filling material as a reuse option. In order to do this, used tires must go through a pulverization process (mechanical or cryogenic), which implies higher energy consumption. The positive environmental impact on resource conservation of co-processing scrap tires in cement kilns is also confirmed by Teller et al. (1999). As previously stated, the use of scrap tires in cement kilns can reduce the need for mining iron due to the iron content of tires (Barlaz et al., 1993; Aliapur, 2010). The Aliapur report compared nine different end-of-life management options and classified them according to certain environmental indicators. Table 3.1 provides a synthesis of these results.

Table 3.1

ENVIRONMENTAL PERFORMANCE CLASSIFICATION (Aliapur, 2010)

Environmental performance	Best 3 options	Worst 3 options
Global warming	Artificial turf, moulded object, energy recovery in cement manufacturing	Infiltration basin, equestrian floor, retention basin
Energy consumption	Artificial turf, steelworks, moulded object	Infiltration basin, equestrian floor, retention basin
Non-renewable resources consumption	Asphalt road pavement, steelworks, moulded object	Infiltration basin, equestrian floor, retention basin
Water consumption	Asphalt road pavement, moulded object, equestrian floor	Infiltration basin, retention basin, steelworks

The use of scrap tires in cement kilns, the artificial turf production process, and incinerators decrease GHG emissions when compared with the use of coal (Fiksel et al., 2010). GHG emissions increase when asphalt road pavement is produced with scrap tires because the procedure requires additional processing steps (Barlaz et al., 1993; Fiksel et al., 2010).

It is possible to obtain NO_x and SO_2 emission reductions when tires are burned in boilers instead of coal; however, particulate matter emissions increase (Barlaz et al., 1993; Fiksel et al., 2010). For asphalt road pavement production with scrap tires, there is a verifiable increase in NO_x and SO_2 emissions (Fiksel et al., 2010). Results differ, however, when it comes to co-processing in cement kilns. Silvestraviciute and Karaliunaite (2006) asserted that burning scrap tires creates the highest amount of direct air emissions, while Fiksel et al. (2010) and a U.S. Environmental Protection Agency report (1991) stated that it minimizes air pollution. Both these studies refer to scrap tires and not to tire derived fuel, which could have a different performance.

The use of used tires in artificial turf production greatly reduces hazardous air pollutants and metal emissions (Fiksel et al., 2010). Co-processing in cement kilns presents the largest metal emissions reduction, while metal emissions increase significantly when scrap tires are combusted in industrial boilers (Fiksel et al., 2010). There is a risk of soil and groundwater metal contamination when used tires are used in the asphalt road pavement production process (Barlaz et al., 1993). According to the U.S. Environmental Protection Agency (1991), dioxins and furans are minimized when scrap tires are burned in industrial boilers or in cement kilns.

The eutrophication potential decreases when tires are used in artificial turf production, industrial boilers, and incinerators (Fiksel et al., 2010). Energy recovery in cement kilns is also considered a low eutrophication potential solution (Aliapur, 2010).

The combustion of used tires in cement kilns does not produce residues since the ashes are incorporated into the clinker (Barlaz et al., 1993; Fiksel et al., 2010; U.S. Environmental Protection Agency, 1991). However, indirect solid waste may be produced in the upstream process (Fiksel et al., 2010). By-products from pyrolysis have a market value (European Environmental Agency, 1996), even though, for example, char needs to be upgraded (U.S. Environmental Protection Agency, 1991). Landfilling presents waste management problems as used tires can stay intact for many years (European Environmental Agency, 1996) and, because they are mainly whole, tires tend to “float” to the top of landfills (U.S. Environmental Protection Agency, 1991).

Installation of artificial turf produced with scrap tires creates concerns about exposure risks for users, but these are within acceptable limits (Fiksel et al., 2010). The reduction of pollutant emissions when tires are burned in cement kilns reduces human health risks in comparison to incineration, where an increased risk to human health has been verified. For combustion in industrial boilers, contrasting effects have been registered (Fiksel et al., 2010). Landfilling can cause mosquito proliferation that can threaten human health (U.S. Environmental Protection Agency, 1991).

Economic Impact

Recycled rubber from tires has a higher cost than other materials, which can limit its application (U.S. Environmental Protection Agency, 1991). Tires used in cement kilns should be supplied for free or, in the best case, a tipping fee could be given to plants to accept them (Barlaz et al., 1993). Scrap tires are, in some cases, bought by cement plants (for instance, cement plants compete with other recycling plants); nonetheless, they result in the cheapest fuel source except for local petroleum coke (U.S. Environmental Protection Agency, 1991).

Large capital expenses and operating costs, however, should be taken into account if cement plants are to use tires (Barlaz et al., 1993; U.S. Environmental Protection Agency, 1991). Capital costs are lower for industrial boilers, but tires compete with cheaper fuels. Furthermore, tires used in industrial boilers are more costly because they must be wire-free; in fact the iron in the tires could be detrimental to the plant (U.S. Environmental Protection Agency, 1991). Considering the economic impact of the use of scrap tires in cement plants, it should also be noted that some industrial boilers cannot accept whole scrap tires, but require tire derived fuel that requires processing and, thus, higher costs.

Pyrolysis also has high capital and operating costs as well as costs to upgrade char (U.S. Environmental Protection Agency, 1991). Landfilling is the cheapest alternative (U.S. Environmental Protection Agency, 1991), although it should be noted that landfilling tires is prohibited in most Canadian provinces. Sustained commercial operations of pyrolysis must still be demonstrated (U.S. Environmental Protection Agency, 1991), while the high capital costs and variability of product quality represent barriers to its application (European Environmental Agency, 1996).

Other Social Impact

Breakthrough findings about the social impact of different end-of-life options for scrap tires were not available in the literature.

3.2.5. Used Lubricating Oil

Although used lubricating oils were included with IC&I residues (Section 3.1), they have been separated into their own category due to the relevant number of documents retrieved.

Environmental and Human Health Impact

Used lubricating oil can be reused, reducing the demand for crude oil (European Union, 2007). Oil regeneration and reuse reaches better resources saving performance than oil use as fuel in cement manufacturing (Fehrenbach, 2005). Lubricating oils wear out after several reusing stages and, therefore, cannot be reused indefinitely. Worn out oils can, however, be combusted in cement kilns and there is at least one cement plant in Canada that uses non-recyclable oils in its operations.

Co-processing of used lubricating oil in cement kilns shows a lower global warming impact than regeneration and reuse (Fehrenbach, 2005). Kanokkantapong et al. (2009) found that energy recovery in industrial boilers and acid clay extraction are end-of-life options for used lubricating oil with a high global warming impact.

Reusing oils avoids pollution of soil, groundwater and surface water, whereas incineration and landfilling have an impact on human health and environment (European Union, 2007).

Although energy recovery in cement manufacturing and incineration provide a positive environmental performance with respect to heavy metal emissions (Kanokkantapong et al., 2009), reuse provides still better results (Fehrenbach, 2005). The acidification potential is highest for acid clay extraction and the lowest for solvent extraction; recovery in cement kilns has a lower acidification potential than recovery in industrial boilers (European Union, 2007). Acidification and nitrification indicators show better results for reuse than for energy recovery in cement kilns (Fehrenbach, 2005).

The eutrophication potential is higher for energy recovery in cement manufacturing than for acid clay extraction and solvent extraction (European Union, 2007).

No data were available about waste generated by these processes.

Economic Impact

Information about the economic impact of these end-of-life management options is missing.

3.2.6. Biomass

Anaerobic digestion, pyrolysis and gasification are suitable end-of-life options for biomass and they are added to the biomass types described in Section 3.1.8.

Environmental and Human Health Impact

Anaerobic digestion provides a higher energy recovery rate than incineration with electricity production (European Union, 2002). Biomass can be substituted for fossil fuels through incineration with electricity production, pyrolysis and gasification (European Union, 2002). Nutrients in biomass can also be recovered when used as fertilizer (European Union, 2002).

Incineration, pyrolysis and gasification of biomass have comparable levels of carbon emissions to air, whereas recycling biomass as fertilizer shows quite lower levels (European Union, 2002). Anaerobic digestion provides CO_2 neutral energy production in the form of electricity and heat (European Union, 2002).

Ozone depletion and acidification levels are higher when biomass is landfilled. Pyrolysis and gasification emit less flue gas than incineration (European Union, 2002). Gasification and pyrolysis also make the retention of metals possible, further reducing the emissions (European Union, 2002).

Gas and pyrolytic oils from gasification and pyrolysis, respectively, contain toxic and carcinogenic compounds, which are dangerous to humans (European Union, 2002).

Economic Impact

Pyrolysis, gasification and anaerobic digestion require waste sorting to ensure the operational suitability of biomass (European Union, 2002), which increases operational costs. When biomass is used as fertilizer or as fuel in incineration with electricity generation, there is no need for sorting; however, the former requires skilled labour and the latter requires extensive capital investments including a flue gas cleaning system (European Union, 2002).

3.2.7. Hazardous Waste

A single document was retrieved about hazardous waste. It found no convincing proof that cement kilns produce additional hazardous waste emissions and that incineration of hazardous waste in specific incinerators, under some hypotheses, is preferable to combustion in rotary kilns (Tukker, 1999). The document also noted the issue of metal emissions from waste with a high metal content. The Tukker study found that there is a knowledge gap about the leaching of metals; this may not be of concern when the metal content of fuel is low, but could be a sensitive question when dealing with fuels with a high metal content.

3.3. Gaps Emerged from Findings Retrieval

In addition to the gaps discussed in Section 2.7, several other gaps emerged during this phase.

With respect to RQ1, very few documents were found that discussed the use of plastic waste in cement kilns. This could be a symptom of the low suitability of plastics as fuel in cement plants due to their chlorine content, which is considered detrimental to the clinker quality. However, more studies dealing with this topic would be helpful for stakeholders. With respect to other waste categories, there were also few hazardous waste documents found.

Much attention has been paid to global warming issues and on pollutant emissions (dioxins, furans, metals, NO_x and SO_2). Of particular concern is the fact that there is not a complete understanding of how dioxin and furan emissions are formed, although most experts are familiar with the conditions required for their formation. The social and health impacts of using alternative fuels in cement plants have also not been thoroughly investigated, even though these are topics of interest to both stakeholders and the general public.

The economic impact of using alternative fuels, as well as the possible technical adaptations that a company must consider, are available in the literature. Although most studies are site specific, an adequate amount of generic knowledge is available. More documentation would, therefore, deepen the existing knowledge.

For RQ2, few documents showed a direct comparison between the use of waste in cement kilns and other end-of-life options.

A relatively large amount of information is available about MSW, sewage and wastewater sludge, and scrap tires, even though that knowledge is often focused on few end-of-life options. Unfortunately, the documentation on plastics, used lubricating oil (and IC&I), and hazardous waste is not adequate. More documents are required about these alternative fuels and about other alternative fuels not included in RQ2 due to the total absence of documents.

End-of-life options for some alternative fuels are only briefly discussed in the available literature. Further study, such as the reuse of scrap tires or the anaerobic digestion of sludge, would be useful to assess the most suitable end-of-life option(s).

3.4. Summary

The findings to both research questions are presented in this section.

Each alternative fuel category was detailed and the findings related to each were analyzed as per the impact categories presented in Section 1.4.

The greatest number of documents found related to the issue of air emissions, such as CO_2, NO_x, SO_2, metals, dioxins and furans. These emissions are, in general, reduced when alternative fuels are used instead of fossil fuels. A fair amount of knowledge was also available on the economic impacts of using alternative fuels, but those findings had to be carefully assessed to avoid site-specific results that could bias the study.

The analysis of the RQ1 findings showed a lack of knowledge about the social impacts of alternative fuels. Moreover, the use of certain alternative fuels, such as plastics and hazardous waste, need to be further investigated.

Among the possible end-of-life options, combustion of waste in cement kilns appears to be one of the best solutions. The waste management hierarchy must be taken into account, which make reuse and recycling the most preferable solutions; however, the advantages of reuse and recycling can often be coupled with combustion in cement kilns once the recycling potential of the residue stream is maximized (e.g., used oil has a limit on the number of times it can be recycled). Disposal of waste in landfills emerged as the worst end-of-life option and, in some cases (e.g., sewage sludge), was illegal.

The number of documents retrieved related to RQ2 was quite low. Further studies are needed to address this problem, with priority given to less-investigated alternative fuels, such as IC&I and hazardous waste.

4

synthesis of findings

The previous section outlined the available evidence for RQ1 and RQ2. While comprehensive, the section required the reader to understand the complexity of the findings. By contrast, Section 4 combines and synthesizes the findings for immediate communication through summary tables, and describes the methodology used to do so.

4.1. Methodology Used for RQ1 Findings

The starting point for the synthesis was the table of narrative findings previously created. The objective of this section was to transform those narrative findings into visual indicators. All findings were substituted with a numeric value in order to aggregate the findings in a comparable and synthetic form and also to indicate a particular tendency for each impact category when using a specific alternative fuel.

In order to do so, the narrative findings were classified as:

- **Positive findings:** Findings that indicate certain advantages deriving from the use of alternative fuels compared to conventional fuels, for the impact category
- **Negative findings:** Findings that indicate certain disadvantages and potential risks deriving from the use of alternative fuels compared to conventional fuels, for the impact category
- **Neutral findings:** Findings that do not show a clear advantage or disadvantage deriving from the use of alternative fuels compared to conventional fuels, for the impact category.

The classification assigned a numeric value, positive, negative or neutral, to each finding, as shown in Table 4.1.

Table 4.1

NUMERIC VALUES ACCORDING TO THE FINDINGS CATEGORY

Finding	Value
Positive	+1
Negative	-1
Neutral	0

Some of the findings compared the alternative fuels with other energy sources. Some of them referred explicitly to a particular fossil fuel such as coal or coke (e.g., the energy content comparable with coal). However, comparisons were frequently made between a specific alternative fuel and an unspecified fossil fuel. Such cases were commonly found in practitioner sustainability reports where the performance of alternative fuels was judged against a mix of fossil fuels because companies actually use a mix of fossil fuels. The findings in the tables specify the fossil fuel(s) with respect to the performance assessed when this information was available. In the other cases, a comparison with generic fossil fuels has been assumed.

Sometimes, findings referred to unspecified limits. These findings were considered as neutral because it was not possible to use them to make a comparison with the use of fossil fuels.

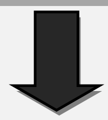
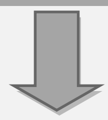
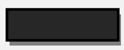
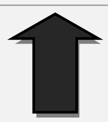
Findings were often extracted from more than one document. In these cases, a +0.2 was added for each additional document that confirmed a previous positive finding. In the case of negative findings, a -0.2 was considered for each additional document. For instance, a finding such as "Decrease of PCDD emissions" cited by four documents is marked by +1.6, i.e., +1 for the first document and +0.2 for the second, the third and the fourth document. The calculation is similar for negative findings. This method gives a measure of the reliability and robustness of specific findings.

In the case of multiple effects aggregated into a single finding, e.g., "Decrease of PCDD and PCDF emissions," each effect was considered separately. The value associated with the finding in that example is thus +2. The results of this phase can be found in Appendices 7.4 and 7.5.

In this way, a numerical value has been associated with each cell of the table. The number was then transformed into a symbol according to the legend in Table 4.2.

Table 4.2

SYMBOLS ASSOCIATED TO THE NUMERIC VALUES FOR RQ1

Range	Symbol (number of documents more than 2)	Symbol (number of documents equal or less than 2)
n ≤-2		
-2< n < -0,5		
-0,5< n < 0,5		
0,5< n < 2		
2 ≤ n		

These five different classes were created to highlight both large and small differences between the performance of alternative fuels and fossil fuels (*see Tables 4.1 and 4.2*).

The brightness of the symbol indicates the number of documents used to derive it. When the findings were derived from one or two documents the symbol is brighter than findings derived from two or more documents. The rationale of this is the need to highlight findings obtained from a few documents, in order to indicate the reliability of the findings and the areas that require further investigation.

4.2. Methodology Used for RQ2 Findings

All findings were converted into numeric values (*see Appendices 7.6 through 7.12*) and then into symbols (*see Tables 4.6 through 4.13*), using a similar methodology and procedure as described in the Section 4.1. In this case, however, a relative performance indicator was deemed useful to compare the several end-of-life options. Therefore, the symbols (*see Table 4.3*) were assigned comparing the numeric values of each alternative fuel for each impact category.

Table 4.3

SYMBOLS USED TO SYNTHESIZE THE FINDINGS OF RQ2

Relative performance	Symbol
Much better	+++
Better	++
Slightly better	+
Indifferent	0
Slightly worse	-
Worse	- -
Much worse	- - -

For RQ2, a table was created that synthesizes the results of the tables relative to specific alternative fuels (*see Table 4.13*). To do this, only six main end-of-life options (the ones common to almost all types of alternative fuels) were considered:

- Reuse
- Recycling
- Energy recovery in cement manufacturing
- Incineration
- Incineration with electricity and/or heat generation
- Landfill

The indicators of each impact category for each end-of-life option were averaged among the alternative fuels. A table with overall numeric values was then generated and, eventually, symbols were substituted for the numeric values as in the previous cases.

4.3. Impacts of Alternative Fuels Combustion for Cement Production

The findings described in Section 3.1 were aggregated to create synthetic tables.
In the case of RQ1, two tables were created: one for environmental and social impacts and one for economic and technical impacts (*see Figure 3.1*).

Table 4.4 synthesizes the findings related to the environmental and social impacts of using alternative fuels in cement manufacturing.

Table 4.4

SYNTHESIS OF FINDINGS RELATED TO ENVIRONMENTAL AND SOCIAL IMPACTS FOR RQ1

	General alternative fuel	Municipal solid waste	Industrial, commercial and institutional residues	Plastics	Sewage sludge	Animal and bone meal	Waste wood	Used Tires	Biomass	Hazardous waste
Resource consumption/ conservation	⬆	⬆	⇧		⇧	⬆	⇧	⬆	⬆	⬆
Global Warming	⬆	⬆	▭	⇧	⬆	⬆	⬆	⬆	⬆	⇧
CACs/Non hazardous air pollutant	⬆	⬆	⬆		▭	⇧		⬇	⇧	
Metals & HAPs	⬆	⬇	⬇	▭	⬇	▭	▭	⬇	⇧	⬆
Operations Waste	⬆	⬆	⬆	⇧	⬆	⬆	⇧	⬆	⇧	
Other Social Impact	⬆				▬	⇧	▭	⇧	⬆	
Environmental impact	⬆	⬆	⬆		⇧	▭	⬆	⬆	⬆	▭

The blank spaces in the table represent gaps in the knowledge that must be addressed with further investigations (*see Section 3.3*). Moreover, the category “General alternative fuel” was added, which includes all the findings not related to a specific alternative fuel, to ensure that the information was retained.

Table 4.4 shows a majority of impact improvement when alternative fuels are used in cement manufacturing instead of fossil fuels.

Resource consumption and conservation improves with the use of alternative fuels; this is due to the avoidance of fossil (or non-renewable) fuel consumption and to the use of components in alternative fuels as raw material substitutes for clinker production. A drawback, in this case, is the potentially high content of chlorine in alternative fuels such as plastics and, sometimes, hazardous waste, which is detrimental to the quality of the finished good. The use of alternative fuels is, thus, consistent with a “closed loop” strategy for industries.

It was largely recognized that, in general, using alternative fuels instead of fossil fuels reduces net GHG emissions, but there are exceptions. For example, an opposite trend occurs in the case of scrap carpets, part of the IC&I residues group, due to the composition of the material; similarly, the trend is not as clear with respect to the use of plastics and hazardous waste. Some of the alternative fuels, to different extents, are considered carbon neutral (e.g., biomass, waste wood and sewage sludge), hence they do not emit more carbon into the atmosphere than the amount sequestered during their life span. In some cases, the combustion of waste in cement kilns avoided landfilling; thus, the fermentation of waste and the subsequent production of methane were prevented.

The environmental impact of the use of alternative fuels, considering criteria air contaminants and non-hazardous air pollutant emissions, was generally lower in comparison to the use of fossil fuels. Used tires were the only alternative fuel that had a major impact in this category. The impact of sewage sludge was neutral with respect to the impact of traditional fuels. Nonetheless, it is possible to manage, and sometimes reduce, some pollutants through technical solutions, e.g., improving the combustion process. This must be considered by cement plant operators to reduce the overall impact.

Metal and hazardous air pollutant emissions presented different trends among the alternative fuels. In general, dioxin and furan emissions decreased when alternative fuels were used; in the case of MSW, however, the results differed. A similar situation was presented for metal emissions, particularly when referring to mercury, which can be very hazardous for human health.

The combustion of alternative fuels in cement kilns decreases the demand for landfills and recovers energy from waste, which avoids disposal problems. MSW has a neutral impact, possibly because the ashes produced by combustion are locked into the clinker and can be used as a raw material substitution.

From the few findings that were available on the social and human health impacts, the impacts depended on the particular alternative fuel used. Hence, every consideration about this point should be fuel-specific.

Other environmental impacts were generally positive. Animal and bone meal and hazardous waste have an impact similar to that of traditional fossil fuels.

Similar to Table 4.4, Table 4.5 describes the economic and technical impacts deriving from the use of alternative fuels in cement kilns.

Table 4.5

SYTHESIS OF MAIN FINDINGS RELATED TO ECONOMIC AND TECHNICAL IMPACTS FOR RQ1

	General alternative fuel	Municipal solid waste	Industrial, commercial and institutional residues	Plastics	Sewage sludge	Animal and bone meal	Waste wood	Used Tires	Biomass	Hazardous waste
Economic Impact	⬆	⬆	⇩	—	⬆	⬆	⬇	⬆	⇧	
Environmental regulatory compliance		⬆ *	⇧		⇧	⬆	⇧	⬆		⇧

* A study reports mercury emissions above the limits

Table 4.5 shows the economic and technical impact. The economic impact is generally positive, with the exception of IC&I residues and waste wood (slightly worse impact than fossil fuels) and plastics (similar impact). It is important to note that these are intended as general trends derived from generic findings; differences may be found in site-specific cases.

Except for hazardous waste, there were technical issues when using alternative fuels in the cement industry that must be considered. In general, there were few technical barriers per se; however, some manufacturing systems would need to be adapted to the requirements of alternative fuels.

The availability of alternative fuels depended on the specific alternative fuel. The availability of biomass, waste wood and plastics is relatively poor, mainly due to competition with other end-of-life management options. Ensuring a steady supply of alternative fuels will be required to expand the practice among cement companies.

4.4. Comparison of End-of-life Management Options for Alternative Fuels

As noted previously, the findings reported in Section 3.2 were aggregated in order to create synthetic tables and provide an answer to RQ2. Each table corresponds to a particular alternative fuel, except for the last one, which summarizes and synthesizes the findings from all previous tables.

The tables do not include all the alternative fuel quoted in the previous tables, but only those for which findings were available in the documents retrieved, namely: MSW (Table 4.6), sewage and wastewater sludge (Table 4.7), plastics (Table 4.8), waste tires (Table 4.9), used lubricating oil (Table 4.10), biomass (Table 4.11), and hazardous waste (Table 4.12). The overall findings are shown in Table 4.13.

Blank cells within the tables indicate a lack of knowledge on the particular type of impact for the specific end-of-life management option (*see Section 3.3*). Some tables were built with very few findings; however, the available findings were recorded to ensure that the knowledge retrieved, even if it was relatively poor, was retained.

Table 4.6 synthesizes the findings about several end-of-life options for MSW. As a general result, energy recovery in cement manufacturing is one of the best end-of-life options, even though the performance in resource consumption and conservation, and metal and hazardous air pollutant emissions can be worse than for other end-of-life options, such as recycling. Beyond the synthesis in the table, it should be noted that there is a lively discussion about the subject within the scientific community, particularly when it comes to air emissions. Recycling and combustion in cement kilns could be combined; in fact, cement manufacturers often choose to use only the post-recycling fraction of MSW. Landfilling should be avoided and incineration discouraged in favour of better end-of-life options.

Table 4.7 shows that energy recovery in cement kilns is one of the best practices for sewage and wastewater sludge, even though, as mentioned before, the metal and hazardous air pollutant emissions need to be analyzed when planning the use of alternative fuels in cement plants. Recovery of sludge in cement kilns presents an advantage due to the availability of the existing infrastructure required. Another environmentally sound end-of-life solution is the use of sludge as fertilizer, although the practice is illegal in some countries if the sludge is not treated.

Information about end-of-life options for plastics (Table 4.8) is limited. However, it seems that the best option is recycling, followed by co-processing in cement kilns. Incineration of plastics is not a suitable solution in terms of waste management.

Energy recovery in cement manufacturing, recycling as artificial turf, and energy recovery in industrial boilers were found to be the best options for scrap tires (Table 4.9). Landfilling or reusing tires in asphalt road pavement appeared to be the worst options.

It was possible to make a few considerations about end-of-life options for used lubricating oil. Table 4.10 shows that reuse is the best option. However, as stated previously, reuse and recovery in cement manufacturing can be combined. In fact, used oils are often reused until they are worn out and finally combusted in cement kilns.

With respect to biomass (Table 4.11), pyrolysis and recycling as fertilizer seem to provide the greatest benefits, even though pyrolysis can cause the formation of toxic and carcinogenic compounds that must be carefully managed. Many negative findings were found with respect to landfilling biomass. Information about energy recovery in cement manufacturing is missing.

Hazardous waste (Table 4.12) was analyzed only for metal and hazardous air pollutant emissions. The results show that incineration in MSW incinerators is better than co-processing in cement kilns; however, standards differ among countries (i.e., the practice is legal in The Netherlands, but illegal in the U.S.).

The aggregated Table 4.13 shows that energy recovery in cement manufacturing and reuse are the best end-of-life management options. Landfilling is the worst for all the impact categories considered except the economic impact.

4.5. Summary

In this section, the findings discussed in Section 3 were synthesized in tables, according to the methodology described. Findings were classified as positive, negative, or neutral. A numerical value was assigned to each of them that supported the scoring of each alternative fuel for each impact category. Scores obtained through only a few documents are highlighted in order to support a correct understanding of the summary tables.

Two tables were created to answer RQ1, one for environmental and social impacts and one for economic and technical impacts. Both tables show a general improvement of the environmental and economic impacts of cement kilns when using alternative fuels instead of fossil fuels. The most positive impacts are in terms of global warming potential and resource conservation, while the main concerns are related to metal and hazardous air pollutant emissions.

For RQ2 a table for each of the alternative fuels considered in Section 3.2 was created. Moreover, a final, highly aggregated table was built to assess each of the most common end-of-life management options against each impact category. The tables show that, in general, reuse and energy recovery in cement manufacturing are the best end-of-life options, while disposal in landfills is the worst.

This section also discussed the main results from the synthetic tables that were used to aggregate the findings found in the retrieved literature.

Table 4.6

SYNTHESIS OF FINDINGS ABOUT END-OF-LIFE OPTIONS COMPARISON FOR MUNICIPAL SOLID WASTE

	Recycling	Recycling (composting)	Energy Recovery in Cement Mfg	Incineration	Incineration w/Electricity Generation	Incineration w/Heat Generation	Incineration w/Electricity and Heat Generation	Landfill	Production of RDF	Co-generation in coal-fired power plant	Biomass combustion system
Resource consumption and conservation	+	+	- -		+	+	+ +	-		-	-
Global Warming	+ +	0	+ + +	+	+	+	0	- -		+ + +	-
CACs/Non hazardous pollutant			0	- -	- - -	- - -	-			0	- -
Metals & HAPs	0		-	- - -	- - -	- - -	- - -	0	-	0	0
Operations Waste	- -	-	+	- -	+	+	+ +	-		-	-
Economic impact			+ +	- -	-	-	+			+	
Health and social impact	+ +	+ + +		-	-	+	-	- -			
Technical feasibility		+	+		+	-	+			-	-

Table Based on 9 Documents

Table 4.7

SYNTHESIS OF FINDINGS ABOUT END-OF-LIFE OPTIONS COMPARISON FOR SEWAGE AND WASTEWATER SLUDGE

	Resource consumption and conservation	Global Warming	CACs/ Non-hazardous pollutant	Metals & HAPs	Operations Waste	Economic impact	Health and social impact	Technical feasbility
Compositing	+				+	+	+	-
Recycling (Agricultural use not composted)	+ +	-		-	+	+	0	
Energy Recovery in Cement Mfg	0	+ +		-	+	+	+	+ +
Incineration	0	-		- - -	+	-	-	+ +
Incineration w/Electricity Generation	0	-		+	+ + +	- -	0	+ +
Landfill		-				-		
Anaerobic digestion	+ + +			- -			+	
Production of biofuel						-		
Direct production of electricity in microbial fuel cells				- -				
Co-generation in coal-fired power plant				0				
Gasification	+			+ + +		-		+
Pyrolisis	0	- -	0	0	+ +	-		+ +
Wet Oxidation		-	0	+	-	+		- -
Hydrothermal processes	+			0				-
Raw material in cement production	0			+		-		
Heat only plant						-		
Cogeneration plant						0		

Table 4.8

SYNTHESIS OF FINDINGS ABOUT END-OF-LIFE OPTIONS FOR PLASTICS

	Recycling	Energy Recovery in Cement Mfg	Incineration	Incineration w/Electricity Generation	Landfill
Resource consumption and conservation	+ + +	+	-	-	- -
Global Warming			-	-	
CACs/Non hazardous pollutant		+			-
Metals & HAPs					-
Operations Waste		+		+	-
Economic impact	+				
Health and social impact					
Technical feasibility					

Table Based on 3 Documents

Table 4.9

SYNTHESIS OF FINDINGS ABOUT END-OF-LIFE OPTIONS FOR USED TIRES

	Reuse	Recycling (use in asphalt road pavement)	Recycling (use in artificial turf)	Recycling (others)	Energy Recovery in Cement Mfg.	Energy Recovery in industrial boilers	Pyrolisis	Incineration	Incineration w/ Electricity Generation	Landfill	Civil engineering applications
Resource consumption and conservation	+	+	+	- -	+ + +	+		-	+		-
Global Warming		-	+ +	- - -	+ +			+			
CACs/Non hazardous pollutant		- -	+ + +	- - -	0	0			-		
Metals & HAPs		-	+ + +		+ + +	+		-		- -	
Eutrophication potential			+ +	- -	+	+		+			
Operations Waste			-	+	+	+ + +	+	+ +		- - -	
Economic impact		-	- -	-	0	+ +	- -		-	+ +	
Health and social impact		-	+	+ +	+ + +	0		- -	+	- -	+
Technical feasibility		-	+		- -	- -	-				

Table Based on 9 Documents

Table 4.10:

SYNTHESIS OF FINDINGS ABOUT END-OF-LIFE OPTIONS FOR USED LUBRICATING OIL

	Reuse	Recycling: Acid clay extraction	Recycling: Solvent extraction	Energy Recovery in Cement Mfg.	Incineration	Energy Recovery in industrial boilers	Incineration w/ Electricity Generation	Landfill
Resource consumption and conservation	+ +							
Global Warming		0		+		-		
CACs/Non hazardous pollutant	+				-			-
Metals & HAPs	+	-	0	+ + +	+ +			
Operations Waste								
Eutrophication potential			-	-				
Economic impact								
Health and social impact	+							
Technical feasibility								

Table Based on 3 Documents

Table 4.11

SYNTHESIS OF FINDINGS ABOUT END-OF-LIFE OPTIONS FOR BIOMASS

	Anaerobic digestion	Recycling: fertilisers	Incineration w/Electricity generation	Pyrolisis	Gasification
Resource consumption and conservation	+	+	+	+	+
Global Warming	+ +	+	-	+	-
CACs/Non hazardous pollutant			-	+ +	+
Metals & HAPs		+		+ + +	+
Operations Waste	-	+	-	-	-
Eutrophication potential					
Economic impact	+	+	+	-	-
Health and social impact					
Technical feasibility				+	+

Table Based on 3 Documents

Table 4.12

SYNTHESIS OF FINDINGS ABOUT END-OF-LIFE OPTIONS COMPARISON FOR HAZARDOUS WASTE

	Municipal solid waste incinerators	Cement kilns
Resource consumption and conservation		
Global Warming		
CACs/Non hazardous pollutant		
Metals & HAPs	+	-
Operations Waste		
Eutrophication potential		
Economic impact		
Health and social impact		
Technical feasibility		

Table Based on 1 Document

Table 4.13

SYNTHESIS OF FINDINGS ABOUT END-OF-LIFE OPTIONS COMPARISON FOR ALTERNATIVE FUELS

	Reuse	Recycling	Energy Recovery in Cement Mfg	Incineration	Incineration w/Electricity and/or Heat Generation	Landfill
Resource consumption and conservation	+ +	+ +	+	0	0	-
Global Warming		0	+ +	0	0	- - -
CACs/Non hazardous pollutant	+ +	-	+	- - -	0	- -
Metals & HAPs	+	0	+	- - -	-	-
Operations Waste		0	+ +	+	+ +	- -
Economic impact		0	+ +	- -	- -	+
Health and social impact	+ +	0	+ +	0	+	- -

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conclusions

The environmental, social, health and economic impacts of cement plants is a major concern for Canadian stakeholders. A switch to alternative fuels could reduce the impact of plants on the environment, communities, and human health as well as bring about economic benefits.

This report analyzed the various impacts of different alternative fuels used in cement kilns and compared them to other possible end-of-life management options. Specifically, it sought to answer the following two questions:

1. What are the environmental, human health, social, and economic implications of using alternative energy sources compared to the use of traditional fossil fuels (i.e., coal, petroleum coke) in cement manufacturing?
2. Considering the net environmental, human health, social and economic aspects, how does the use of alternative energy sources in cement manufacturing compare with other end-of-life/waste management options such as reuse, recycling, energy recovery, or disposal?

A literature search was performed to retrieve the most relevant documents for the two research questions. The search uncovered 76 documents relevant to the first question and 41 relevant to the second. These documents were deeply analyzed and the findings were extracted and arranged in tables.

Using a specific methodology, the findings were used to create summary tables as a way to answer the research questions that drove this study.

The summary tables highlighted some important results from the study:

- There is no single alternative fuel that can be considered better than the others, although the impact on global warming, resource consumption and conservation was found to be generally lower (i.e., more favourable) for alternative fuels than for fossil fuels.
- In some cases, for the majority of the alternative fuels considered, issues emerged when metal and hazardous air pollutant emissions were investigated. To manage this issue, it is important that waste composition be controlled prior to use in a cement kiln.
- Cement manufacturing operations and fuel availability must be considered when choosing an alternative fuel.
- Among the various end-of-life management options, and according to the findings presented, the use of alternative fuels in cement manufacturing generally provided the greatest benefits as compared with other end-of-life options, along with recycling. However, this is a general trend and represents a qualitative more than quantitative analysis; specific analyses need to be undertaken when considering a specific alternative fuel. On the other hand, landfilling is the worst option.

The results of this study synthesized and compared the existing knowledge about the use of alternative fuels in cement production and created a reference point for policy makers and other stakeholders. At the same time, this study highlighted the information gaps that emerged from the analysis, providing direction on areas where additional research is needed.

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7

appendices

This section includes:

Appendix 7.1 Methodology adopted for literature retrieval

Appendix 7.2 List of data sources

Appendix 7.3 List of relevant documents

Appendix 7.4 Findings table with values for environmental and social impact for RQ1

Appendix 7.5 Findings table with values for economic and technical impact for RQ1

Appendix 7.6 Findings table with values for municipal solid waste for RQ2

Appendix 7.7 Findings table with values for sewage and wastewater sludge for RQ2

Appendix 7.8 Findings table with values for plastics for RQ2

Appendix 7.9 Findings table with values for used tires for RQ2

Appendix 7.10 Findings table with values for used lubricating oil for RQ2

Appendix 7.11 Findings table with values for biomass for RQ2

Appendix 7.12 Findings table with values for hazardous waste for RQ2

Appendix 7.13 References used in findings tables for RQ1

Appendix 7.14 References used in findings tables for RQ2

7.1 Methodology Adopted for Literature Retrieval

Insights into the methodology used in the literature retrieval are provided here, followed by the results from the literature search phase.

Introduction

In the first phase of this project, the relevant documents on which the systematic review was based were reviewed. The document search was performed considering four groups of documents:

- Academic papers
- Institutional reports
- Practitioner reports
- Case studies

The search strings used in the selected databases, relative to the specific research questions, are shown in Table 7.1:

Table 7.1

SEARCH STRINGS

RESEARCH QUESTION 1: What are the environmental, human health, social, and economic implications of energy substitution using alternative energy sources in comparison to the use of traditional fossil fuels (i.e. coal, petroleum coke) in cement manufacturing?	***1. Cement manufacturing AND Alternative fuels AND Environmental Impact*** (“cement manufactur*” OR “cement plant*” OR “cement kiln” OR “cement product*” OR “cement process*” OR “clinker product*” OR ((“blast furnace” OR “rotary kiln”) AND “cement”)) AND (“renewable energy source” OR “alternative energy source” OR “RDF” OR “waste derived fuel” OR “alternative fuel” OR “tires” OR “tyres” OR “plastics” OR “sewage sludge” OR “biomass” OR “biosolids” OR “MSW” OR “residue*” OR “meat meal” OR “bone meal” OR “solvent*” OR “used oil*” OR “photographic waste” OR “oil emulsion*” OR “animal fat” OR “filter cake” OR “wood” OR “energy recovery”) AND (“GHG” OR “greenhouse gas*” OR “carbon dioxide” OR “CO2” OR “nitrous oxide” OR “NOx” OR “SO2” OR “sulphur oxide” OR “environmental impact” OR “environmental performance” OR “emission*” OR “air pollution” OR “dioxin” OR “furans” OR “hazardous metal*” OR “volatile*” OR “PCB” OR “PAH*” OR “BTEX” OR “HCl” OR “HF” OR “combustion waste” OR “risk material” OR “dust” OR “acidification” OR “eutrophication” OR “PCDD” OR ”PCDF” OR “PM”)
	2. Cement manufacturing AND Alternative fuels AND Economic Impact (“cement manufactur*” OR “cement plant*” OR “cement kiln” OR “cement product*” OR “cement process*” OR “clinker product*” OR ((“blast furnace” OR “rotary kiln”) AND “cement”)) AND (“renewable energy source” OR “alternative energy source” OR “RDF” OR “waste derived fuel” OR “alternative fuel” OR “tires” OR “tyres” OR “plastics” OR “sewage sludge” OR “biomass” OR “biosolids” OR “MSW” OR “residue*” OR “meat meal” OR “bone meal” OR “solvent*” OR “used oil*” OR “photographic waste” OR “oil emulsion*” OR “animal fat” OR “filter cake” OR “wood” OR “energy recovery”) AND (“cost*” OR “economic return” OR “economic viability” OR “economic sustainability” OR “cost*benefit analysis” OR “economic impact”)
	3. Cement manufacturing AND Alternative fuels AND Health Impact (“cement manufactur*” OR “cement plant*” OR “cement kiln” OR “cement product*” OR “cement process*” OR “clinker product*” OR ((“blast furnace” OR “rotary kiln”) AND “cement”)) AND (“renewable energy source” OR “alternative energy source” OR “RDF” OR “waste derived fuel” OR “alternative fuel” OR “tires” OR “tyres” OR “plastics” OR “sewage sludge” OR “biomass” OR “biosolids” OR “MSW” OR “residue*” OR “meat meal” OR “bone meal” OR “solvent*” OR “used oil*” OR “photographic waste” OR “oil emulsion*” OR “animal fat” OR “filter cake” OR “wood” OR “energy recovery”) AND (“health” OR “illness” OR “disease” OR “carcinogen” OR “cancer”)

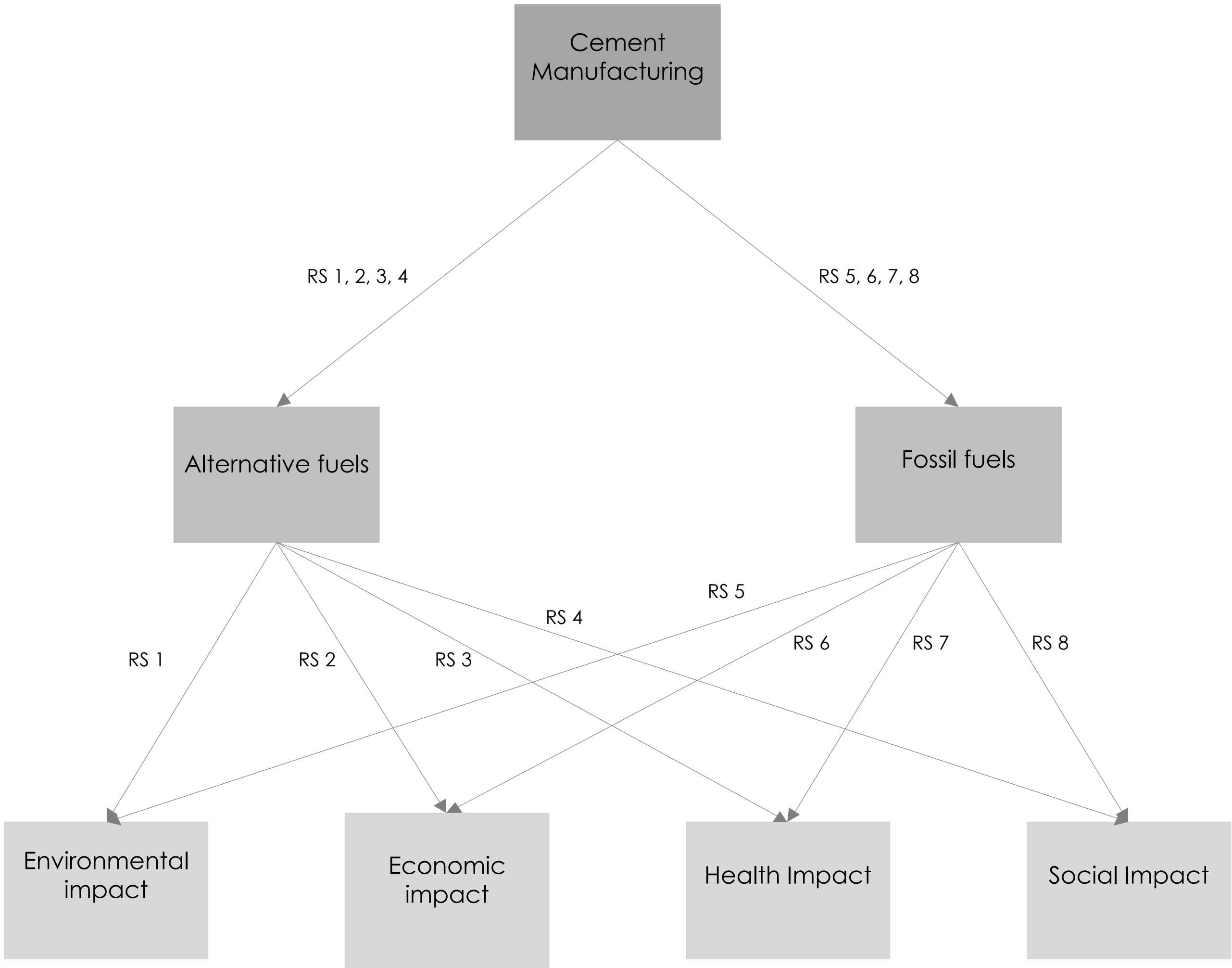
	4. Cement manufacturing AND Alternative fuels AND Social Impact (“cement manufactur*” OR “cement plant*” OR “cement kiln” OR “cement product*” OR “cement process*” OR “clinker product*” OR ((“blast furnace” OR “rotary kiln”) AND “cement”)) AND (“renewable energy source” OR “alternative energy source” OR “RDF” OR “waste derived fuel” OR “alternative fuel” OR “tires” OR “tyres” OR “plastics” OR “sewage sludge” OR “biomass” OR “biosolids” OR “MSW” OR “residue*” OR “meat meal” OR “bone meal” OR “solvent*” OR “used oil*” OR “photographic waste” OR “oil emulsion*” OR “animal fat” OR “filter cake” OR “wood” OR “energy recovery”) AND (“local development” OR “occupation” OR “employment” OR “economic development” OR “social impact”)
	5. Cement manufacturing AND Fossil fuels AND Environmental Impact (“cement manufactur*” OR “cement plant*” OR “cement kiln” OR “cement product*” OR “cement process*” OR “clinker product*” OR ((“blast furnace” OR “rotary kiln”) AND “cement”)) AND (“coal” OR “petroleum coke” OR “pet*coke” OR “heavy fuel oil” OR “natural gas” OR “oil refinery flare gas” OR “fossil fuel”) AND (“GHG” OR “greenhouse gas*” OR “carbon dioxide” OR “CO2” OR “nitrous oxide” OR “NOx” OR “SO2” OR “sulphur oxide” OR “environmental impact” OR “environmental performance” OR “emission*” OR “air pollution” OR “dioxin” OR “furans” OR “hazardous metal*” OR “volatile*” OR “PCB” OR “PAH*” OR “BTEX” OR “HCl” OR “HF” OR “combustion waste” OR “risk material” OR “dust” OR “acidification” OR “eutrophication” OR “PCDD” OR ”PCDF” OR “PM”)
	6. Cement manufacturing AND Fossil fuels AND Economic Impact (“cement manufactur*” OR “cement plant*” OR “cement kiln” OR “cement product*” OR “cement process*” OR “clinker product*” OR ((“blast furnace” OR “rotary kiln”) AND “cement”)) AND (“coal” OR “petroleum coke” OR “pet*coke” OR “heavy fuel oil” OR “natural gas” OR “oil refinery flare gas” OR “fossil fuel”) AND (“cost*” OR “economic return” OR “economic viability” OR “economic sustainability” OR “cost*benefit analysis” OR “economic impact”)
	7. Cement manufacturing AND Alternative fuels AND Health Impact (“cement manufactur*” OR “cement plant*” OR “cement kiln” OR “cement product*” OR8 “cement process*” OR “clinker product*” OR ((“blast furnace” OR “rotary kiln”) AND “cement”)) AND (“coal” OR “petroleum coke” OR “pet*coke” OR “heavy fuel oil” OR “natural gas” OR “oil refinery flare gas” OR “fossil fuel”) AND (“health” OR “illness” OR “disease” OR “carcinogen” OR “cancer”)
	8. Cement manufacturing AND Alternative fuels AND Social Impact (“cement manufactur*” OR “cement plant*” OR “cement kiln” OR “cement product*” OR “cement process*” OR “clinker product*” OR ((“blast furnace” OR “rotary kiln”) AND “cement”)) AND (“coal” OR “petroleum coke” OR “pet*coke” OR “heavy fuel oil” OR “natural gas” OR “oil refinery flare gas” OR “fossil fuel”) AND (“local development” OR “occupation” OR “employment” OR “economic development” OR “social impact”)
RESEARCH QUESTION 2: Considering net environmental, human health, social and economic aspects, how does the use of alternative energy sources in cement manufacturing compare with other end-of-life / waste management options such as reuse, recycling, different types of energy recovery, and ultimately disposal?	***End-of-life options AND Cement AND Energy AND Alternative fuels*** (“reus*” OR “recycl*” OR “remanufactur*” OR “recover*” OR “treatment” OR “waste management” OR “end*of*life management” OR “3Rs” OR “landfill” OR “incineration” OR “disposal” OR “discharg*” OR “energy production” OR “energy recovery” OR “energy generation” OR “electricity generation” OR “electricity production”) AND (“cement”) AND (“energy” OR “fuel”) AND (“renewable energy source” OR “alternative energy source” OR “RDF” OR “waste derived fuel” OR “alternative fuel” OR “tires” OR “tyres” OR “plastics” OR “sewage sludge” OR “biomass” OR “biosolids” OR “MSW” OR “residue*” OR “meat meal” OR “bone meal” OR “solvent*” OR “used oil*” OR “photographic waste” OR “oil emulsion*” OR “animal fat” OR “filter cake” OR “wood” OR “energy recovery”)

For RQ1, seven clusters of keywords to be considered in the document search were identified. The seven clusters were assembled to create eight specific research strings as shown in the previous table. Figure 7.1 illustrates the clusters and how they were linked to obtain the research strings. This scheme was used to obtain all the relevant documents, for both alternative and fossil fuels, already grouped by specific type of impact.

Specific keywords to distinguish between LCA and non-LCA studies were not included. An “ex-post” refinement of the documents retrieved was performed to include the LCA studies published from 2009, to complete the study done by Martineau et al. (2010)

Figure 1

SEARCH STRINGS (RS) SCHEME



For RQ2, one search string that included the main end-of-life options for the considered alternative fuels was created. The keywords “cement”, “energy” and “fuel” were also taken into account to obtain documents related to the production of energy from alternative fuels in cement manufacturing. This limited the number of retrieved papers but enabled us to find the truly relevant papers to compare the use of alternative fuels in cement production with the other end-of-life options.

The results of the document search phase are detailed below, along with an assessment of these for each group of documents. The relevant documents are listed in Appendix 7.3.

Academic Papers

The search for academic papers was split for the two research questions. In this phase, abstract and title were analyzed.

During the search, the terms used for alternative fuel types in the available literature seem to be quite dispersed. For some papers, therefore, a further analysis was required to define the category of the mentioned alternative fuel (e.g., emulsions, hazardous waste, refused derived fuel, waste derived fuels, waste oils). The content of the wastes, particularly for municipal solid waste, sewage sludge, and biosolids, needs to be analyzed. For example, some papers evaluate the municipal solid waste including plastics and hazardous liquid wastes, while some of them just consider solid waste.

However, the classification in Section 1.2 has been kept for synthesis and generalization issues, leaving detailed analysis to further specific studies.

Academic Papers – RQ1

Figure 7.2 represents the results of the document search from academic databases. After the search was performed, 903 documents were obtained of which 104 were considered relevant (see Figure 7.2). More than half of the retrieved documents were irrelevant for the research question. The most relevant documents were retrieved from ScienceDirect and Scopus.

As shown in Figure 7.3, 31 documents were duplicates (existing in more than one database) and seven of them merely described the technical issues about the use of alternative fuels or contained process modelling issues. One of the documents described a case study where the cement plant uses wind energy as a substitute for electric energy. Three documents did not give quantitative results and three were available only on websites without a clear definition of the methodology adopted. Twenty-three of the documents discussed general frameworks related to the cement industry such as total emissions in country levels, regulations related to the industry, general technological aspects of cement kilns, or generally described alternative energy use in the cement sector without making any specific analysis of a specific alternative fuel.

From the 36 papers remaining, four were removed after a further refinement of results. The resulting 32 papers analyzed alternative fuel use and/or made a comparison between alternative and traditional fuel use in cement manufacturing. All 32 papers contain quantitative results.

Number of papers according to the type of alternative fuels:

- 5 sewage sludge and biosolids
- 5 end-of-life tires
- 7 municipal solid waste
- 2 emulsions
- 5 hazardous wastes
- 1 wood
- 2 carpet residues
- 1 waste oils
- 1 plastics
- 1 shredder residues
- 3 RDF
- 2 meat and bone meal
- 2 various fuels (a mix of animal meal, end-of-life tires, solvents, etc)

Figure 7.2

DOCUMENT SEARCH RESULTS FROM ACADEMIC DATABASES FOR RQ1

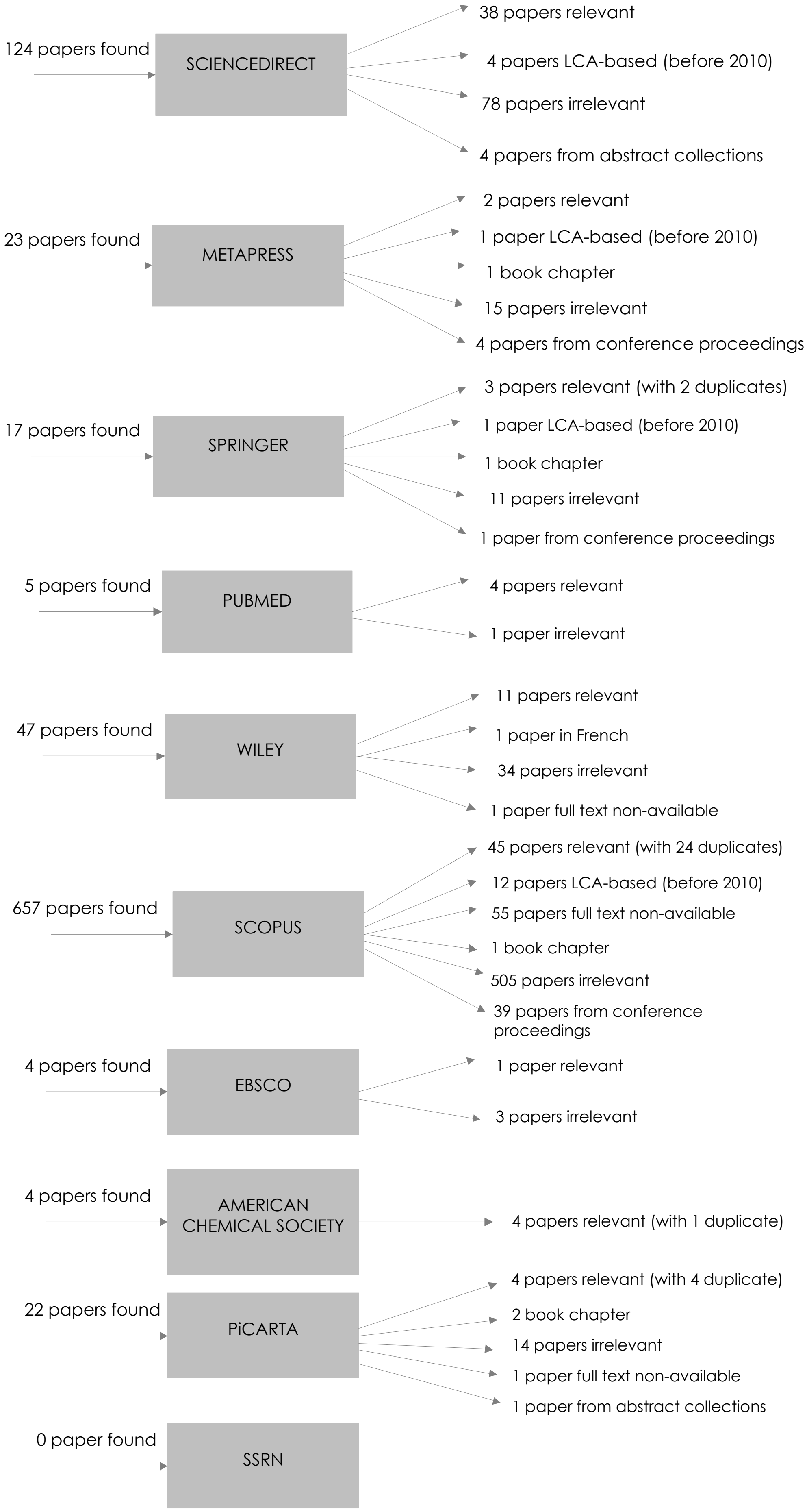
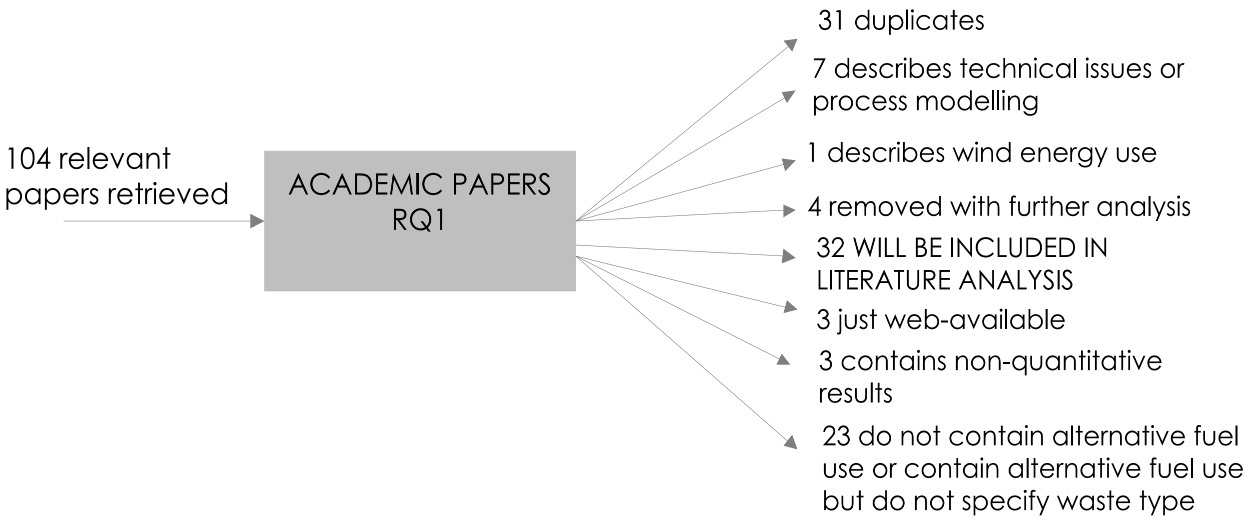


Figure 7.3

PROPERTIES OF THE RETRIEVED RELEVANT ACADEMIC PAPER FOR RQ1



Number of papers according to the analyzed impact categories:[3]

- 15 on PCDD/PCDF emissions
- 11 on heavy metals emissions
- 6 on CO_2 emissions
- 8 on other emissions
- 7 on economic impacts
- 4 on health impacts

No academic papers focused on social impact analysis.

Academic Papers – RQ2

Figure 7.4 show the academic papers retrieved from each database. The document search produced 662 papers, of which 22 were considered relevant. The most relevant documents were retrieved from ScienceDirect and Scopus.

After deleting nine duplicates, one paper dealing with technical feasibility, and two papers that did not make a comparison between an end-of-life option and the use of alternative fuels in cement kilns, 10 papers were retained and included in the literature analysis (*see Figure 7.5*).

Of these, the list below shows the types of alternative fuels, end-of life options, and dimensions of comparison found.

Number of papers according to the type of alternative fuels:

- 1 solid recovered fuels (SRF) derived from municipal solid waste (MSW)
- 2 plastic solid waste (PSW)
- 3 wastewater sludge
- 1 municipal solid wastes
- 1 RDF (residue derived fuel) from municipal solid wastes
- 2 waste tires

[3] Some of the papers analyze more than one impact

Types of end-of life options (other than combustion in cement kiln):

- Incineration
- Co-incineration (in coal-fired power plants, MSW incinerator, biomass combustion system)
- Energy recovery in other manufacturing plants (e.g., in pulp and paper mill boilers)
- Re-extrusion
- Recycling (mechanical or chemical)
- Use in road pavement
- Agricultural reuse
- Thermal processes (e.g., pyrolysis, wet oxidation, gasification)
- Hydrothermal treatment
- Anaerobic digestion
- Production of RDF
- Production of biofuels

From a preliminary assessment of the relevant papers, gaps in literature were identified. The research did not produce papers on the comparison of the use of animal / bone meal, IC&I residues, and waste wood in cement kilns with other end-of-life options. Moreover, for each of the retrieved types of alternative fuels, only a subset of the listed end-of-life options was compared with the use in cement kilns in the retrieved papers. No paper was found that compared health and social dimensions, and the economic dimension of comparison was not discussed for each type of end-of-life option and alternative fuel.

Figure 7.4

DOCUMENT SEARCH RESULTS FROM ACADEMIC DATABASES FOR RQ2

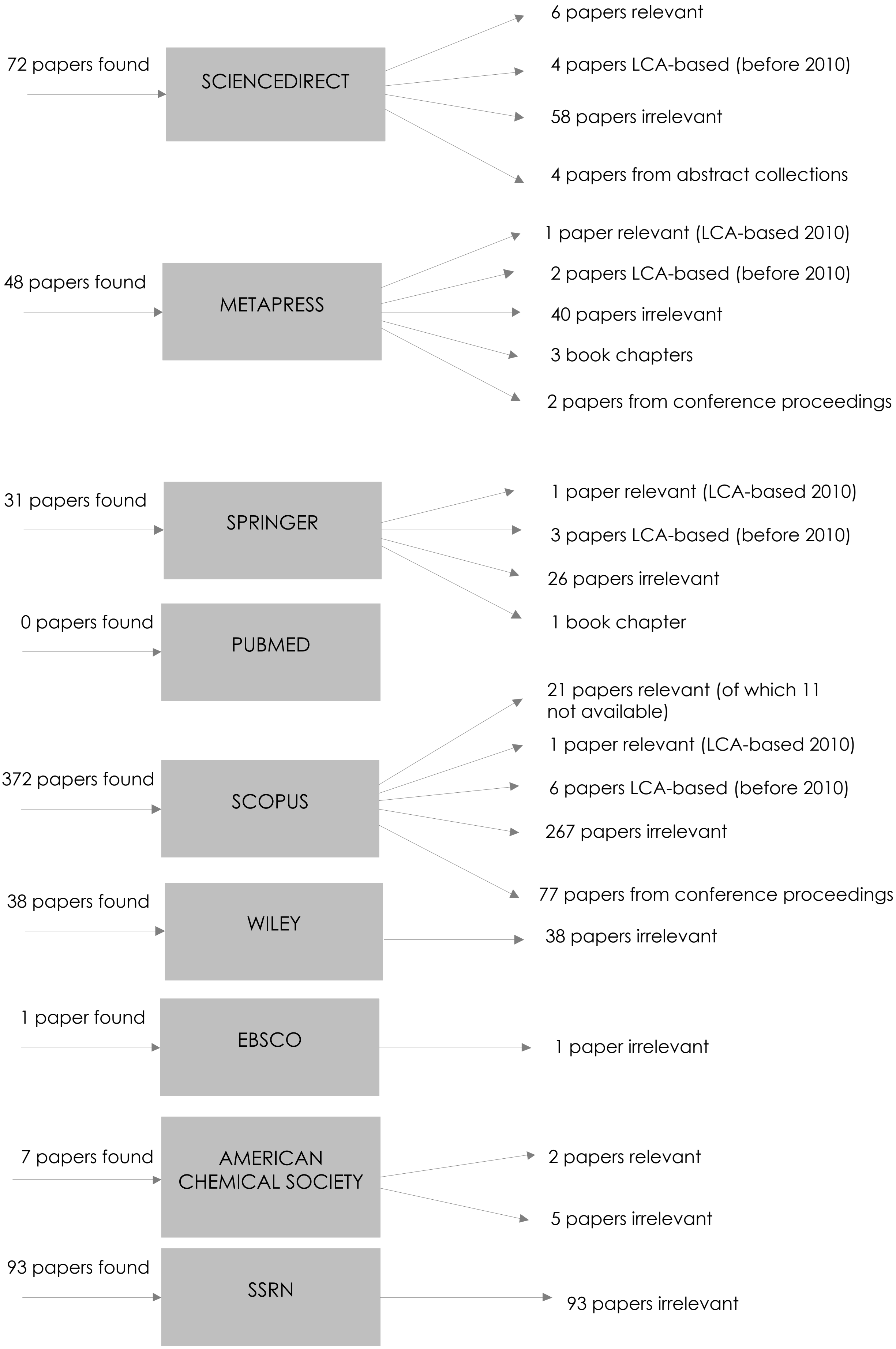
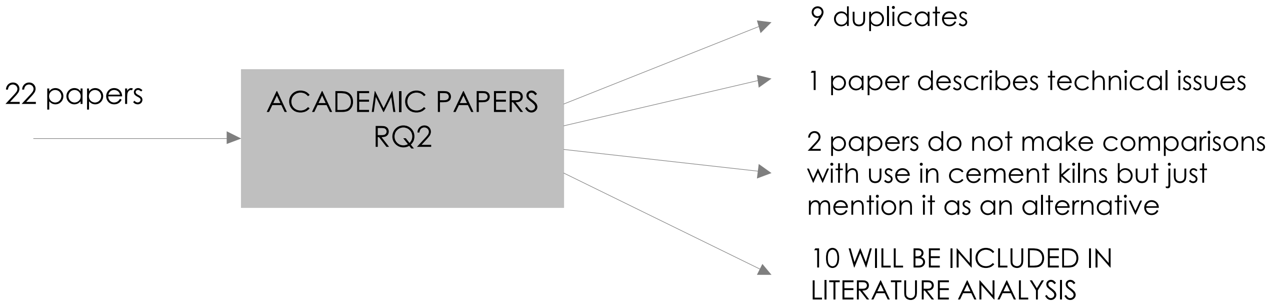


Figure 7.5

PROPERTIES OF THE RETRIEVED RELEVANT ACADEMIC PAPER FOR RQ2



Institutional Reports

The literature assessment of institutional reports was carried out separately for the two research questions. Consultancy organizations were included in this group due to the similarity of documents available. The search strings used for the academic papers retrieval were applied in this case due to the different kind of documents searched and to the search string limits of some databases. However, the previous search strings were used as inspiration for this research. Table 7.2 details the search strings used. Given that institutional reports do not have an abstract, when possible, the search was performed only on the title (rather than on the full report) to be consistent with the process for the academic papers. The search strings used differed due to the particular institution. The search in cement-related institutions was not performed for RQ2 because this group of institutions did not appear in other end-of-life options for alternative fuels other than incineration in cement kilns.

The institutions considered in this phase were grouped as follows:

- **Consulting organizations:** Boston Consulting Group, Deloitte, McKinsey Quarterly
- **Industry associations:** Cement Association of Canada, CEMBUREAU, Portland Cement Association
- **Governmental organizations:** UK Environmental Agency, European Environmental Agency, UK Health Protection Agency, U.S. Environmental Protection Agency, European Commission
- **Intergovernmental organizations:** World International Energy Agency
- **Professional membership bodies:** Institute of Environmental Management and Assessment
- **Research organizations:** Worldwatch Institute, MIT Sloan Management Review, International Institute of Sustainable Development

Table 7.2

SEARCH STRINGS USED IN THE INSTITUTIONAL DATABASES

Institution	String for RQ1	String for RQ2
Boston Consulting Group	(“cement manufacturing” OR “cement plant” OR “cement kiln” OR “cement production” OR “cement process” OR “clinker production” OR ((“blast furnace” OR “rotary kiln”) AND “cement”))	(“reus*” OR “recycl*” OR “remanufactur*” OR “recover*” OR “treatment” OR “waste management” OR “end*of*life management” OR “3Rs” OR “landfill” OR “incineration” OR “disposal” OR “discharg*” OR “energy production” OR “energy recovery” OR “energy generation” OR “electricity generation” OR “electricity production”) AND (“cement”) AND (“energy” OR “fuel”) AND (“renewable energy source” OR “alternative energy source” OR “RDF” OR “waste derived fuel” OR “alternative fuel” OR “tires” OR “tyres” OR “plastics” OR “sewage sludge” OR “biomass” OR “biosolids” OR “MSW” OR “residue*” OR “meat meal” OR “bone meal” OR “solvent*” OR “used oil*” OR “photographic waste” OR “oil emulsion*” OR “animal fat” OR “filter cake” OR “wood” OR “energy recovery”)
Cement Association of Canada	renewable energy AND alternative energy	-
Deloitte	cement	waste
UK Environmental Agency	cement AND energy	waste management AND cement AND (energy OR fuel)
CEMBUREAU (European Cement Association)	renewable energy AND alternative energy	-
European Commission	cement AND (alternative energy OR renewable energy)	waste management
European Environment Agency	cement AND (alternative energy OR renewable energy)	waste management
Institute of Environmental Management and Assessment	cement AND (alternative energy OR renewable energy)	waste OR waste management
International Energy Agency	cement (in publications)	waste, refuse derived, residue, waste management, tires, tyres (in renewable fuels)
International Institute of Sustainable Development	(“cement manufactur*” OR “cement plant*” OR “cement kiln” OR “cement product*” OR “cement process*” OR “clinker product*” OR ((“blast furnace” OR “rotary kiln”) AND “cement”)) AND ("alternative energy" OR "renewable energy")	(“reus*” OR “recycl*” OR “remanufactur*” OR “recover*” OR “treatment” OR “waste management” OR “end*of*life management” OR “3Rs” OR “landfill” OR “incineration” OR “disposal” OR “discharg*” OR “energy production” OR “energy recovery” OR “energy generation” OR “electricity generation” OR “electricity production”) AND (“cement”) AND (“energy” OR “fuel”) AND (“renewable energy source” OR “alternative energy source” OR “RDF” OR “waste derived fuel” OR “alternative fuel” OR “tires” OR “tyres” OR “plastics” OR “sewage sludge” OR “biomass” OR “biosolids” OR “MSW” OR “residue*” OR “meat meal” OR “bone meal” OR “solvent*” OR “used oil*” OR “photographic waste” OR “oil emulsion*” OR “animal fat” OR “filter cake” OR “wood” OR “energy recovery”)
McKinsey Quarterly	cement AND energy	waste AND energy
MIT Sloan Management	cement AND renewable energy,	waste OR waste management

Review	cement AND alternative energy	
Portland Cement Association	("cement manufactur*" OR "cement plant*" OR "cement kiln" OR "cement product*" OR "cement process*" OR "clinker product*" OR (("blast furnace" OR "rotary kiln") AND "cement")) AND ("renewable energy source" OR "alternative energy source" OR "RDF" OR "waste derived fuel" OR "alternative fuel" OR "tires" OR "tyres" OR "plastics" OR "sewage sludge" OR "biomass" OR "biosolids" OR "MSW" OR "residue*" OR "meat meal" OR "bone meal" OR "solvent*" OR "used oil*" OR "photographic waste" OR "oil emulsion*" OR "animal fat" OR "filter cake" OR "wood" OR "energy recovery")	-
UK Health Protection Agency	cement AND energy	("reus*" OR "recycl*" OR "remanufactur*" OR "recover*" OR "treatment" OR "waste management" OR "end*of*life management" OR "3Rs" OR "landfill" OR "incineration" OR "disposal" OR "discharg*" OR "energy production" OR "energy recovery" OR "energy generation" OR "electricity generation" OR "electricity production")
U.S. Environmental Protection Agency	("cement manufactur*" OR "cement plant*" OR "cement kiln" OR "cement product*" OR "cement process*" OR "clinker product*" OR (("blast furnace" OR "rotary kiln") AND "cement")) (in clean fuels)	MSW, organic material, solvents, scrap tires, used oil
Worldwatch Institute	cement	waste AND energy AND cement

Institutional Reports – RQ1

For RQ1, 612 documents were retrieved, 19 of which were considered as potentially relevant for the research. Search results from the institutional databases are detailed in Figure 7.6.

In general, the information available in the retrieved documents referred to the environmental performances of burning alternative fuels in cement kilns and the thermodynamic properties of the alternative fuels, such as the heating value or the substitution rate respect to fossil fuels. Little information was available about the costs related to the use of alternative fuels in cement kilns and no information was found concerning the social impact of using alternative fuels.

Several types of alternative fuels were cited in the institutional reports, with prevalence towards the use of scrap tires and liquid and solid waste.

The majority of the relevant documents were published after 2005, with only three documents published between 2001 and 2004.

Finally, the majority of the selected reports belonged to two institutions: the UK Environmental Agency and the Portland Cement Association.

Institutional Reports – RQ1

For RQ2, 308 documents were retrieved, 16 of which were considered potentially relevant, as shown in Figure 7.7.

The retrieved documents mainly dealt with municipal solid waste, which differs in composition for the majority of papers. The end-of-life options considered were: recycling, landfilling, incineration and composting. Information in these documents referred to the economic impact and to the environmental impact of the end-of-life options. Only one document dealt with the social impact of the particular end-of-life option considered. Some of the documents retrieved also included one or more case studies.

The span of publishing year did not show a particular trend. The European Union and the U.S. Environmental Protection Agency provided the majority of the documents.

Figure 7.6

DOCUMENT SEARCH RESULTS FROM INSTITUTIONAL DATABASES FOR RQ1

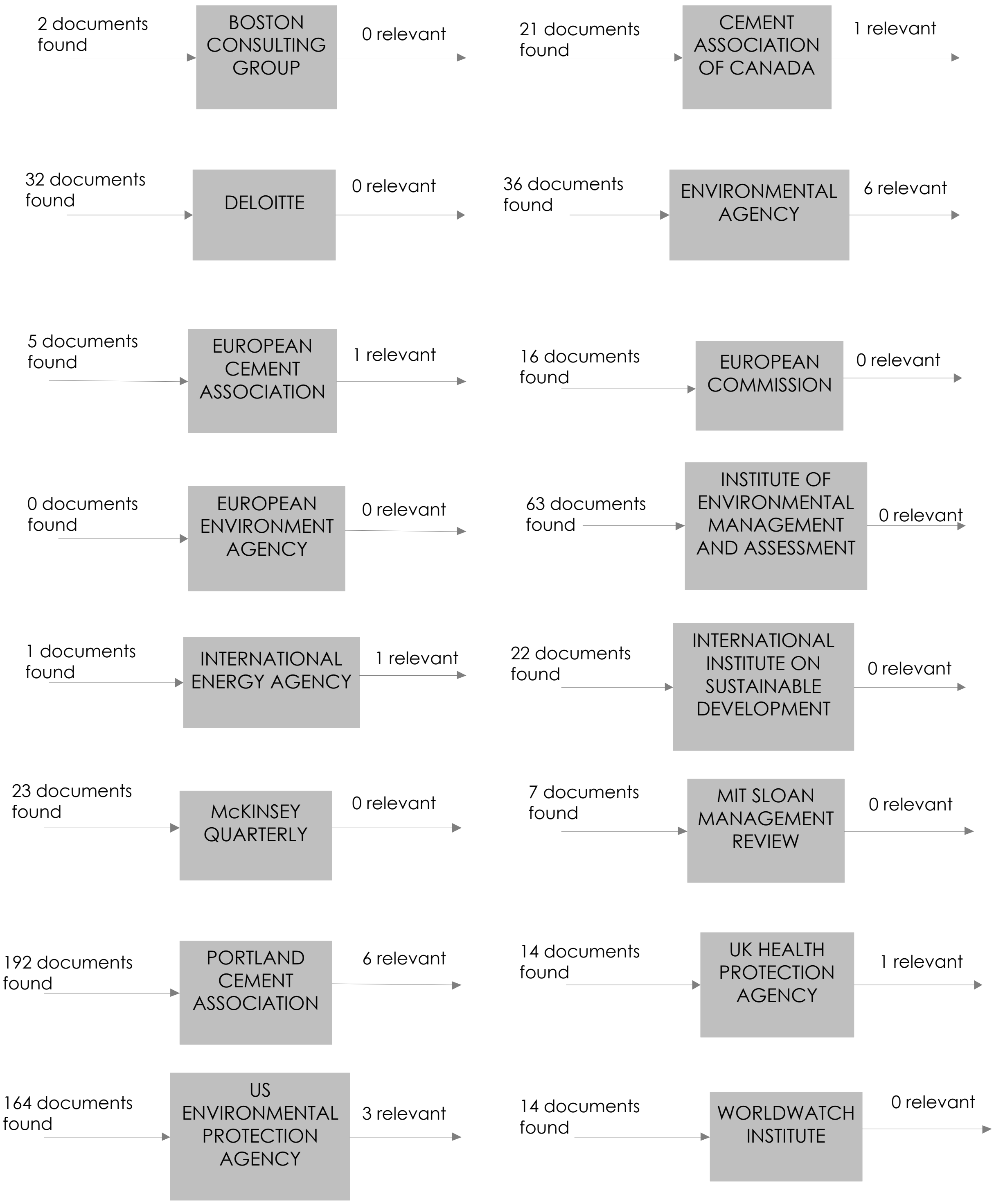
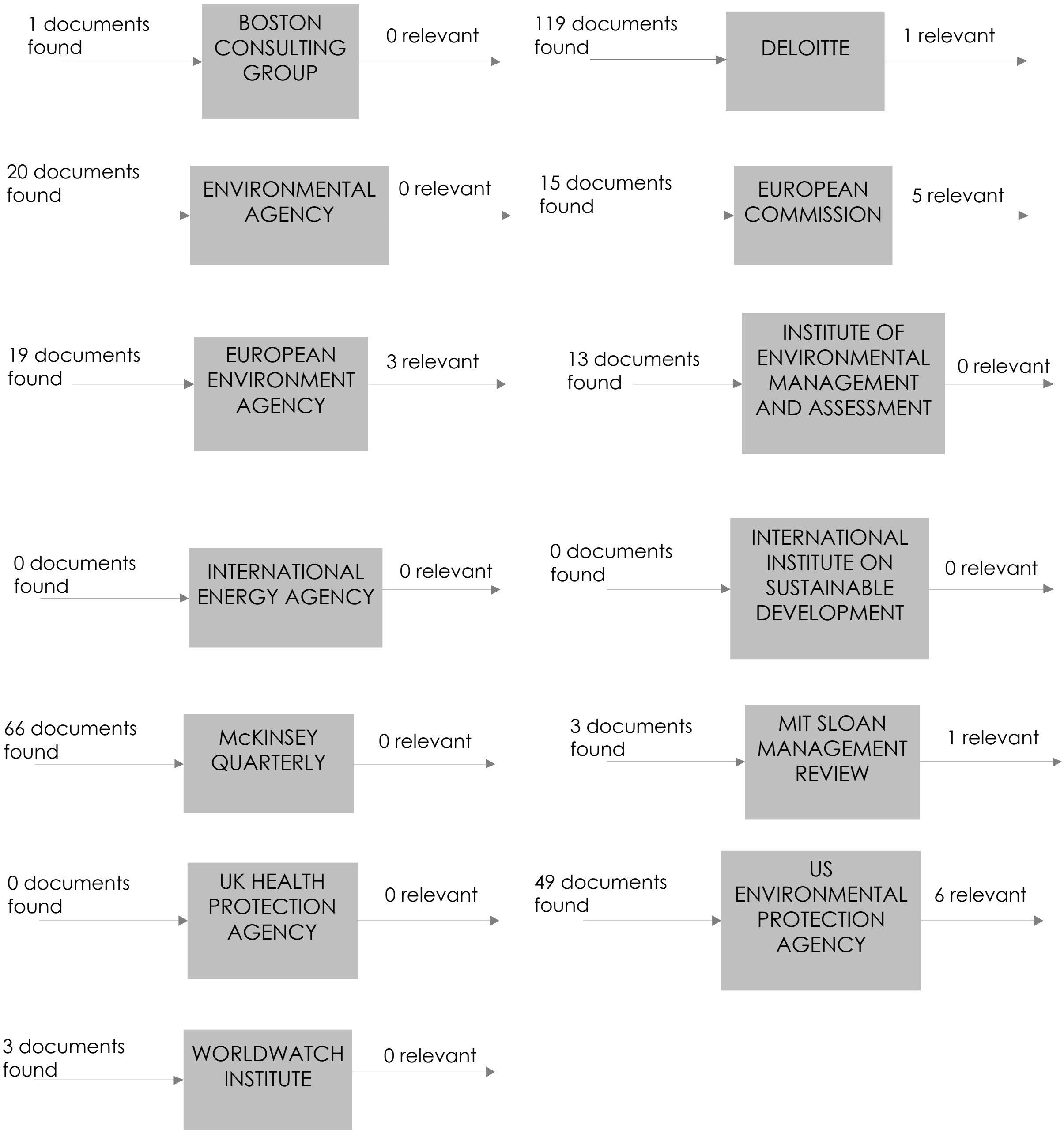


Figure 7.7

DOCUMENT SEARCH RESULTS FROM INSTITUTIONAL DATABASES FOR RQ2

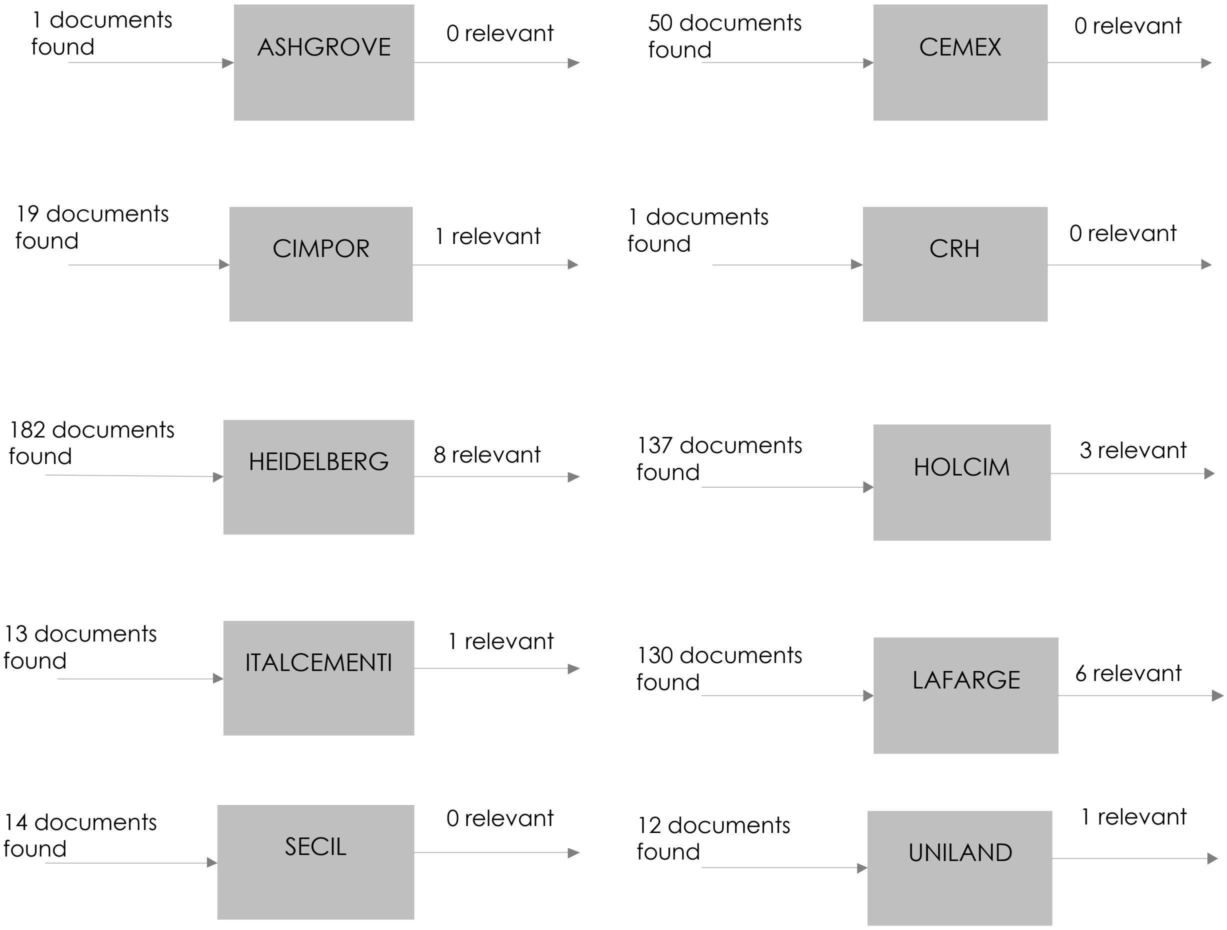


Practitioner Reports

The research for documents in the practitioner databases was performed only for RQ1. In fact, it was assumed that information about other end-of-life options for alternative fuels would not be available in practitioner publications. At the end of the research, 559 documents were collected, but only 20 of them were considered potentially relevant, as shown in Figure 7.8.

Figure 7.8

DOCUMENT SEARCH RESULTS FROM PRACTIONER DATABASES



SECIL UNILAND documents

Most of the retrieved publications included case studies that described the effect of using alternative fuels in cement kilns, giving general insights into the environmental and economic impact. Some of the relevant documents were practitioner sustainability reports. These reports included detailed data about emissions, but these were averaged data, which made it difficult to separate the contribution of alternative and fossil fuels to the total emissions.

The main alternative fuels considered in the relevant practitioner documents were biomass and scrap tires.
During the research, other types of documents such as press releases or website pages were found but were not included in order to maintain a high quality level of research.

Almost all the relevant documents were published between 2007 and 2009, which proves that there is an increasing interest by companies in the use of alternative fuels for cement kilns. LaFarge and Heidelberg were the main contributors to the collection of potentially relevant publications.

Some cement industry journals (such as "World Cement" or "International Cement Review") were not included in this study since they were either not available in the databases searched or were not electronically available.

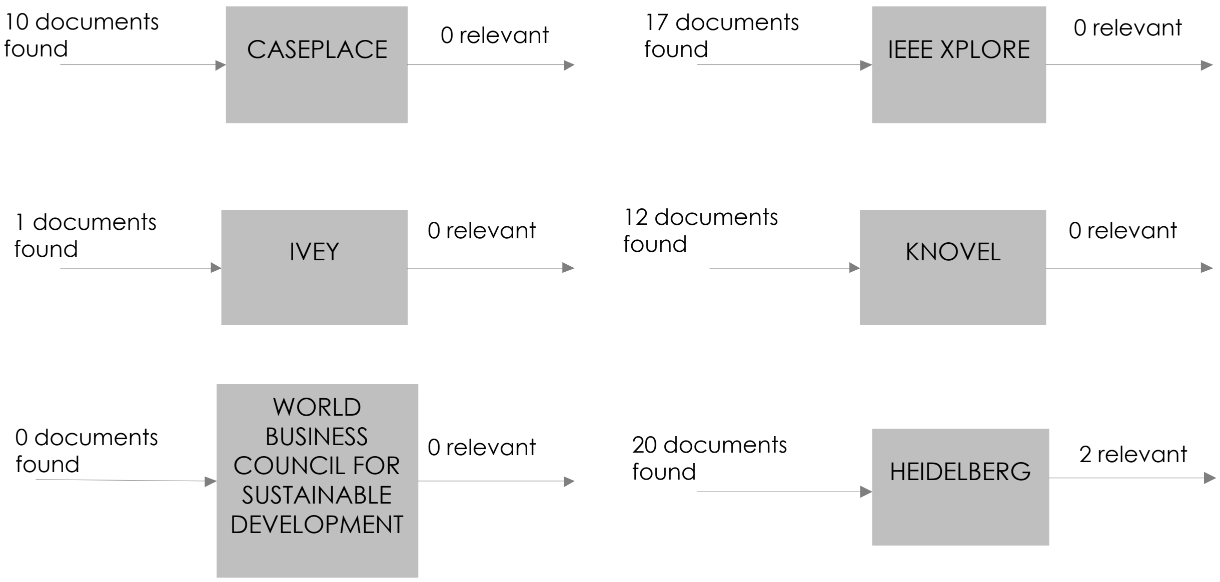
Case Studies

Very few documents dealing with the use of alternative fuels were found in case study databases. Nevertheless, case studies were available on the Heidelberg website, which has a specific section for them, and were included in this section. Only stand-alone case studies were considered in this category. Other case studies were included in the practitioner and institutional reports but since they were described within the report, they were considered as part of the relevant report. Sixty case studies were retrieved, only two of which were considered potentially relevant for the research (Figure 7.9). The search for case studies was limited to RQ1.

The two case studies retrieved (found in the Heidelberg database but with no publication dates) did not provide an in-depth analysis of the use of alternative fuels in cement kilns; however, they were considered relevant due to the general information given about economic and social impact.

Figure 7.8

DOCUMENT SEARCH RESULTS FROM CASE STUDY DATABASES



Other Documents

Documents suggested by the Guidance Committee and the LCA studies from the previous phase (Martineau et al., 2010) were included in the literature assessment.

List of Relevant Documents

Appendix 7.3 lists the relevant documents retrieved, divided by type.

7.2. List of Data Sources

Several data sources from a broad selection were used to identify non-LCA research as well as new LCA research (not included in phase I). The data sources searched were classified as: (i) academic papers, (ii) institutional reports, (iii) practitioner reports, and iv) case studies.

(i) Academic papers

American Chemical Society Publications : http://pubs.acs.org/

British Medical Journal: http://www.bmj.com/

California Management Review: http://cmr.berkeley.edu/

Caspur: http://periodici.caspur.it

EBSCOhost: http://search.ebscohost.com/

Elsevier (http://www.sciencedirect.com)

Emerald (http://www.emeraldinsight.com)

Google scholar (http://scholar.google.com)

Harvard Business Review (http://hbr.org/)

Jstor (http://www.jstor.org/)

MetaPress (http://www.metapress.com)

PiCarta (http://picarta.pica.nl)

PubMed Central (http://www.ncbi.nlm.nih.gov/pmc/)

Scopus (http://www.scopus.com/home.url)

Springer (http://www.springerlink.com)

SSRN (http://papers.ssrn.com/)

Wiley (http://www.wiley.com)

(ii) Institutional reports

Boston Consulting Group (http://www.bcg.com/)

Cement Association of Canada (http://www.cement.ca/)

Deloitte (http://www.deloitte.com/)

UK Environment Agency (http://www.environment-agency.gov.uk/)

European Cement Association (http://www.cembureau.be/)

European Commission (http://ec.europa.eu/environment/index_en.htm)

European Environment Agency (http://www.eea.europa.eu/)

Institute of Environmental Management & Assessment (http://www.iema.net/)

International Energy Agency (http://www.iea.org/)

International Institute for Sustainable Development (http://www.iisd.org/)

McKinsey Quarterly (http://www.mckinseyquarterly.com/)

MIT Sloan Management Review (http://sloanreview.mit.edu/)

Portland Cement Association (http://www.cement.org/)

U.K. Health Protection Agency (http://www.hpa.org.uk/)

U.S. Environmental Protection Agency (http://www.epa.gov/)

Worldwatch Institute (http://www.worldwatch.org/)

(iii) Practitioner reports

Ash Grove (http://www.ashgrove.com/)

Cemex (http://www.cemex.com/)

Cimpor (http://www.cimpor.com/)

CRH (http://www.crh.ie/)

Heidelberg (http://www.heidelbergcement.com/global/en/company/home.htm)

Holcim (http://www.holcim.it/)

Italcementi (http://www.italcementi.it/)

Lafarge (http://www.lafarge.com/)

Secil (http://www.secil.pt/default_en.asp)

Uniland (http://www.uniland.es/unilandwebfront/en/asp/pro_cem.asp)

(iv) Case studies

CasePlace (http://www.caseplace.org/)

Google Scholar (http://scholar.google.com)

IEEE Xplore (http://ieeexplore.ieee.org/Xplore/guesthome.jsp)

Knovel (http://why.knovel.com/)

World Business Council for Sustainable Development (http://www.wbcsd.org/)

Various practitioners' sources (Italcementi, AshGrove, etc.)

7.3. List of Relevant Documents

7.3.1. Relevant Academic Papers – RQ1

Abad, E., Martínez, K., Caixach, J., Rivera, J., (2004), "Polychlorinated Dibenzo-p-dioxin/Polychlorinated Dibenzofuran Releases into the Atmosphere from the Use of Secondary Fuels in Cement Kilns during Clinker Formation," *Environmental Science and Technology*, Volume 38, Pages 4734-4738.

Boughton, B. (2007), "Evaluation of Shredder Residue as Cement Manufacturing Feedstock," *Resources, Conservation and Recycling*, Volume 51, Issue 3, Pages 621-642.

Carrasco, F., Bredin, N., Heitz, M. (2002), "Gaseous contaminant emissions as affected by burning scrap tires in cement manufacturing," *Journal of Environmental Quality*, Volume 31, Pages 1484-1490.

Cartmell, E., Gostelow, P., Riddell-Black, D., Simms, N., Oakey, J., Morris, J., Jeffrey, P., Howsam, P., Pollard, S.J. (2006), "Biosolids - A Fuel or a Waste? An Integrated Appraisal of Five Co-Combustion Scenarios with Policy Analysis," *Environmental Science and Technology*, Volume 40, Pages 649-658.

Chaala, A., Roy, C. (2003), "Recycling of Meat and Bone Meal Animal Feed by Vacuum Pyrolysis," *Environmental Science and Technology*, Volume 37, Pages 4517-4522.

Cheung, W.H., Choy, K.K.H., Hui, D.C.W, Porter, J.F., Mckay, G. (2006), "Use of Municipal Solid Waste for Integrated Cement Production," *Developments in Chemical Engineering and Mineral Processing*, Volume 14, Issues 1-2, Pages 193-202.

Cheung, W.H., Vinci K.C. Lee, McKay, G. (2007), "Minimizing Dioxin Emissions from Integrated MSW Thermal Treatment," *Environmental Science & Technology,* Volume 41, Issue 6, Pages 2001-2007.

Choy, K.K.H., Ko, D.C.K., Cheung, W.H., Fung, J.S.C., Hui, D.C.W., Porter, J.F., Mckay, G. (2004), "Municipal Solid Waste Utilization for Integrated Cement Processing with Waste Minimization: A Pilot Scale Proposal," *Process Safety and Environmental Protection*, Volume 82, Issue 3, Pages 200-207.

Conesa, J.A., Gálvez, A., Mateos, F., Martín-Gullón, I., Font, R. (2008), "Organic and inorganic pollutants from cement kiln stack feeding alternative fuels," *Journal of Hazardous Materials*, Volume 158, Issues 2-3, Pages 585-592.

Cook, A., Kemm, J. (2004), "Health impact assessment of proposal to burn tyres in a cement plant," *Environmental Impact Assessment Review*, Volume 24, Issue 2, Pages 207-216.

Denis, S., Renzoni, R., Fontaine, J.L., Germain, A., Corman, L., Gilson, P. (2000), "Experimental evaluation of emission factors of cement kilns burning hazardous wastes," *Toxicological and Environmental Chemistry*, Volume 74, Pages 155-163.

Eckert Jr., J.O., Guo, Q., Moscati, A.F. (1999), "Mass balance of toxic metals in cement and aggregate kilns co-fired with fossil and hazardous waste-derived fuels," *Environmental Engineering Science*, Volume 16, Number 1, Pages 31-56.

Ehrlich, C., Noll, G., Kalkoff, W.D., Baumbach, G., Dreiseidler, A. (2007), "PM10, PM2.5 and PM1.0—Emissions from industrial plants—Results from measurement programmes in Germany," *Atmospheric Environment*, Volume 41, Issue 29, Pages 6236-6254.

Garg, A., Smith, R., Hill, D., Longhurst, P.J., Pollard, S.J.T., Simms, N.J. (2009), "An integrated appraisal of energy recovery options in the United Kingdom using solid recovered fuel derived from municipal solid waste," *Waste Management*, Volume 29, Issue 8, Pages 2289-2297.

Genon, G., Brizio, E. (2008), "Perspectives and limits for cement kilns as a destination for RDF," *Waste Management*, Volume 28, Issue 11, Pages 2375-2385.

Giannopoulos, D., Kolaitis, D.I., Togkalidou, A., Skevis, G., Founti, M.A. (2007), "Quantification of emissions from the co-incineration of cutting oil emulsions in cement plants – Part I: NOx, CO and VOC," *Fuel*, Volume 86, Issues 7-8, Pages 1144-1152.

Giannopoulos, D., Kolaitis, D.I., Togkalidou, A., Skevis, G., Founti, M.A. (2007), "Quantification of emissions from the co-incineration of cutting oil emulsions in cement plants – Part II: Trace species," *Fuel*, Volume 86, Issue 16, Pages 2491-2501.

Hart, J.R. (1994), "Comparison of Emissions from Burning Hazardous Waste in a Dry-Process Cement Kiln with Emissions from Burning Conventional Fossil Fuels," *Hazardous Waste and Hazardous Materials*, Volume 11, Number 1, Pages 193-199.

Hashimoto, S., Fujita, T., Geng, Y., Nagasawa, E. (2010), "Realizing CO2 emission reduction through industrial symbiosis: A cement production case study for Kawasaki," *Resources, Conservation and Recycling,* Volume 54, Issue 10, Pages 704-710.

Karstensen K.H. (2008), "Formation, release and control of dioxins in cement kilns," *Chemosphere*, Volume 70, Issue 4, Pages 543-560.

Kleppinger, E.W. (1993), "Cement clinker: An environmental sink for residues from hazardous waste treatment in cement kilns," *Waste Management*, Volume 13, Issue 8, Pages 553-572.

Konopa, S.L., Mulholland, J.A., Realff, M.J., Lemieux, P.M. (2008), "Emissions from carpet combustion in a pilot-scale rotary kiln: comparison with coal and particle-board combustion," *Journal of the Air and Waste Management Association*, Volume 58, Pages 1070-1076.

Lamb, C.W., Miller, F.M., Roth, A., Dellinger, B., Sidhu, S. (1994), "Detailed determination of organic emissions from a preheater cement kiln co-fired with liquid hazardous wastes," *Hazardous Waste and Hazardous Materials*, Volume 11, Number 1, Pages 201-216.

Lee, V.K.C., Cheung, W.H., McKay, G. (2008), "PCDD/PCDF reduction by the co-combustion process," *Chemosphere*, Volume 70, Issue 4, Pages 682-688.

Lee, V.K.C., Kwok, K.C.M., Cheung, W.H., McKay, G. (2007), "Operation of a municipal solid waste co-combustion pilot plant," *Asia-Pacific Journal of Chemical Engineering*, Volume 2, Pages 631-639.

Lemieux, P., Stewart, E., Realff, M., Mulholland, J.A. (2004), "Emissions study of co-firing waste carpet in a rotary kiln," *Journal of Environmental Management*, Volume 70, Issue 1, Pages 27-33.

Mlakar, T., Horvat, M., Vuk, T., Stergaršek, A., Kotnik, J., Tratnik, J., Fajon, V. (2010), "Mercury species, mass flows and processes in a cement plant," *Fuel*, Volume 89, Issue 8, Pages 1936-1945.

Mokrzycki, E., Uliasz-Bochenczyk, A., Sarna, M. (2003), "Use of alternative fuels in the Polish cement industry," *Applied Energy*, Volume 74, Issues 1-2, Pages 101-111.

Nadal, M., Schuhmacher, M., Domingo, J.L. (2009), "Cost–benefit analysis of using sewage sludge as alternative fuel in a cement plant: a case study," *Environmental Science and Pollution Research*, Volume 16, Number 3, Pages, 322-328.

Prisciandaro, M., Mazziotti, G., Veglió, F. (2003), "Effect of burning supplementary waste fuels on the pollutant emissions by cement plants: a statistical analysis of process data," *Resources, Conservation and Recycling*, Volume 39, Issue 2, Pages 161-184.

Sarofim, A.F., Pershing, D.W., Dellinger, B., Heap, M.P., Owens, W.D. (1994), "Emissions of metal and organic compounds from cement kilns using waste derived fuels," *Hazardous Waste and Hazardous Materials*, Volume 11, Number 1, Pages 169-192.

Schuhmacher, M., Nadal, M., Domingo, J.L. (2009), "Environmental monitoring of PCDD/Fs and metals in the vicinity of a cement plant after using sewage sludge as a secondary fuel," *Chemosphere*, Volume 74, Issue 11, Pages 1502-1508.

van Loo, W. (2008), "Dioxin/furan formation and release in the cement industry," *Environmental Toxicology and Pharmacology*, Volume 25, Issue 2, Pages 128-130.

Walker, N., Bazilian, M., Buckley, P. (2009), "Possibilities of reducing CO2 emissions from energy-intensive industries by the increased use of forest-derived fuels in Ireland," *Biomass and Bioenergy*, Volume 33, Issue 9, Pages 1229-1238.

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7.3.2. Relevant Academic Papers – RQ2

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7.3.3. Relevant Institutional Reports – RQ1

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7.4. Findings Table with Values for Environmental and Social Impact for RQ1

7.4.1. General alternative fuel

Resource consumption / conservation	a) Reduce the use of fossil fuels and raw materials [1,2,12,15,19,20,21,27,36,38] **+2,8** b) Inorganic ash used as raw material for clinker [1,2,11,12,34] **+1,8** c) Diversify energy mix [29,34,38] **+1,4**
Global Warming	a) Reduce potential methane generation [1,2,12,27,28,38] **+2** b) Reduce CO2 emissions [1,2,12,13,19,21,27,28,29,33,38] **+3**
CACs/Non hazardous air pollutant	a) No influence on SO2 emissions [2] **0** b) Not higher NOx emissions, sometimes lower [2,8,11,19,21] **+1,8** c) SO2 emissions depend also on the fuel [21] **0**
Metals & HAPs	a) Complete destruction of organic compound [2,11,13,34,36] **+1,8** b) Neutralization of acid gases and HCl [2,11] **+1,2** c) No difference in PCDD/PCDF emissions [2,25,28] **0** d) PCDD/PCDF independent on the use of fuel [28] **0** e) HCl independent from the fuel used [2] **0** f) Emission of HCl [21] **0** g) Refractory metals are absorbed by the clinker [11] **+1** h) Volatile metals (Hg,Tl) not absorbed completely in the clinker, to be controlled in substitute fuels [11] **-1** i) Lower PCDD/PCDF than coal [38] **+2**
Operations Waste	a) Reduce hazardous ash residues [1,2] **+1,2** b) No production of liquid residue from gas cleaning [2] **+1** c) Dust emissions do not vary with specific fuel [2] **0** d) Ashes incorporated in the clinker [28] **+1** e) Decrease demand for landfill [1,2,12,15,21,27,28,33,34,38] **+2,8** f) Destruction of hazardous waste [1,28] **+1,2** g) Reduce volume of waste [1,15] **+1,2** h) Waste with negligible HV disposal [1] **0** i) Avoid improper disposal of waste [12,28,29] **+1,4** j) Waste intake let reduce production costs [13] **+1**
Other Social Impact	a) Negligible impact on public health whether using conventional or substitute fuels [11] **0** b) Level of social acceptance can strongly affect local uptake [12] **0** c) Level of social acceptance can affect operations [28] **0** d) Recycling of waste creates new job [34] **+1**
Environmental impact	a) Reduce potential groundwater pollution [1] **+1** b) Substitute fuel is no more polluting than conventional fuel [11,36] **0** c) Effect of switching from coal/coke to natural gas is more significant for emissions reduction than switching to alternative fuels [12] **0** d) Reduction of stack emissions [20] **+1** e) No change in stack emissions [28] **0** f) All the emissions except NOx are dependent on raw materials [28] **0**

7.4.2. Municipal and commercial waste, PASr, PASi waste, RDF, WDF

Resource consumption / conservation	a) Reduction of use of fossil fuels [21,24,52] **+1,4**
Global Warming	a) Reduction of net CO2 emissions [7,19,21,24,38,44,52] **+2,2** b) Reduction of methane emissions [38] **+1**
CACs/Non hazardous air pollutant	a) Decrease of NOx [7,24,44,53,59] **+1,8** b) Decrease of NOx (PASr) [56] **+1** c) Decrease of SO2 [7,44,53,59] **+1,6** d) Decrease of SO2 (PASr) [56] **+1** e) Decrease of particulate [7] **+1** f) Decrease in CO emissions [59] **+1** g) Decrease in CO emissions (PASr) [56] **+1** h) HCl, SOx and NOx under best practical means <u>limit</u> [71] **0** i) Emissions depend on RDF composition [44] **0**
Metals & HAPs	a) Full combustion of organic matter [24] **+1** b) Reduction of HCl emissions [53,59] **+1,2** c) Decrease of HCl emissions (PASr) [56] **+1** d) Reduction of HF emissions [53,59] **+1,2** e) Reduction of PCDD [41,53,59,60,71] **+1,8** f) Reduction of PCDF [41] **+1** g) Doubling of HCl emissions (PASi) [56] **-1** h) Increase of chloride [44] **-1** i) Solid fuels result in more organic or PIC emissions than liquid ones. [69] **0** j) No change in As and Cd in use of PASi [56] **0** k) Decrease of Zn in use of PASi [56] **+1** l) Increase in Cr, Pb and Cu in use of PASi [56] **-3** m) Dust emission increase in use of PASr [56] **-1** n) Heavy metal group I and II are under <u>limits</u> [60, 71] **0** o) Increase on Hg, Pb, Cd compared to coke and coal. [5, 68] **-3,6** p) Increase on Cd, Hg, Tl compared to coke. [44] **-3** q) Decrease in Cd, and Tl compared to coal. [44] **+2** r) For all metal emissions, in simulation case, results remain under the <u>limits</u> [44] **0** s) PCDD/F remain under limits, however it was not possible to understand the impact of RDF[44] **0** t) Some danger may arise for metals due their transfer factors [44] **0** u) Increase in Zn [68] **-1** v) Decrease in Ba. [68] **+1** w) Increase on PCDD/PCDF [68] **-2**
Operations Waste	a) Dust disposal problem [7] **-1** b) No waste from storage and handling [24] **+1** c) Most of ashes incorporated within the clinker [24] **+1** d) Small quantities of waste generated by the maintenance of infrastructure [24] **-1** e) None of the waste management options is found to be global advantageous [7] **0** f) Recovery of waste [7] **+1** g) Reduction of MSW quantities to landfill [7,8,21,24,53] **+1,8**
Other Social Impact	
Environmental impact	a) Reduction of total impact of emissions to air [7,38] **+1,2** b) Reduce transport impact [24] **+1** c) All emissions but CO2 unaffected [24] **0** d) No change in emissions to water [24] **0** e) No change in emissions to land [24] **0**

7.4.3. Industrial, commercial and institutional residues

Resource consumption / conservation	a) ASR, CSOS, SC: Raw material value to replace mined material [38] **+1** b) Solvents: Reduction of use of fossil fuels [73] **+1**
Global Warming	a) Increase of CO_2 emissions (carpet waste) [65] **-1** b) Reduction of CO_2 emissions (solvents, filter cake, paint sludge, fluff) [74] **+1**
CACs/Non hazardous air pollutant	a) Waste liquids from photo processing are used as reagents to decrease NOx emissions [5] **+1** b) Reduction of SO_2 emissions [5,7] **+1,2** c) Reduction of NOx emissions [7,45,73] **+1,4** d) No change in particulate [7] **0** e) Increase of CO [7] **-1** f) Uncertainty about increase/decrease of CO [7] **0** g) SC: Potential increase of NOx [38] **-1** h) CSOS: PAH are not an issue [38] **0** i) After 53% of added cutting oil emulsion, the NO level starts to increase [45] **0** j) Decrease on CO for cutting oil emulsion [45] **+1** k) Increase in NO for carpet waste [49,65] **-1,2** l) Increase in CO for Carpet waste [49,65] **-1,2** m) In the case of waste oil use, NOx, SO_2, CO decrease. [51] **+3** n) Decrease in SO_2 in waste carpet use [65] **+1**
Metals & HAPs	a) No change in PCDD/PCDF emissions [5,7] **0** b) Increase of HCl [5,7] **-1,2** c) Increase of HF [5] **-1** d) No significant change in heavy metal emissions [5,7] **0** e) Small reduction in VOCs [5] **+1** f) ASR can contain metal pollutant [38] **-1** g) CH_2O increase slightly for cutting oil emulsion. [45] **-1** h) For cutting oil emulsions use, the PCDD/F levels are under limits [47] **0** i) Emulsifiable cutting oils do not seem to carry a prohibitive metal loading [47] **0** j) Slight increase in PAH and benzene for carpet waste [49]. **-2** k) Decrease in Hg for waste oil use [51] **+1** l) Reduction of heavy metal emissions with solvents, except for ethanol [73] **+1**
Operations Waste	a) Ashes incorporated within the clinker [49] **+1** b) Burning solvent liquid fuel in cement kiln is better than incineration [7] **0** c) Recycling SLF is preferable to incineration [7] **0** d) Plasterboard diverted from landfill [20] **+1** e) Solvents: avoid disposal problem [21] **+1** f) Chemicals: completely safe thermal recovery [35] **+1** g) ASR, SC: Lowers landfill demand [38] **+1**
Other Social Impact	
Environmental impact	a) Reduction of total impact of emissions to air [7] **+1** b) Reduction of overall impact with solvents [73] **+1** c) Favourable impact (solvents, filter cake, paint sludge, fluff) [74] **+1**

7.4.4. Plastics

Resource consumption / conservation	
Global Warming	a) Reduction of landfill gas emissions [38] **+1**
CACs/Non hazardous air pollutant	
Metals & HAPs	a) HCl emissions [21] **0** b) Chlorinated plastics can increase PCDD/PCDF emissions [38] **0**
Operations Waste	a) Avoid disposal problem [21,38] **+1,2**
Other Social Impact	
Environmental impact	

7.4.5. Sewage sludge

Resource consumption / conservation	a) Preservation of limestone [17] **+1** b) Preservation of coal [17] **+1**
Global Warming	a) CO_2 emissions are climate neutral [2,17,20,21,33,38, 43, 58, 61] **+2,6** b) Effective way to reduce GHG [12] **+1** c) Reduction of CO_2 emissions [74] **+1**
CACs/Non hazardous air pollutant	a) Decrease of NO_x [38] **+1** b) Increase of SO_2 [61] **-1**
Metals & HAPs	a) High levels of Hg may create problems [8] **-1** b) HCl under limits [39] **0** c) HF under limits [39] **0** d) PCDD/PCDF under limits **0** [39,43] e) No correlation with metal emissions [39] **0** f) Emission of class I and II heavy metals under limit [43] **0** g) Increase of dust [61] **-1** h) Increase of heavy metals [61] **-1**
Operations Waste	a) Mineral components are fit for the clinker [17] **+1** b) Heavy metals are incorporated in the clinker [17] **+1** c) Energy recovery [17,33] **+1,2** d) Sustainable disposal [17,33,38] **+1,4**
Other Social Impact	a) No competition with nutrition of humans/animals [17] **+1** b) Issue with public perception [38] **-1** c) Decrease of cancer probability for heavy metals [42] **+1** d) Increase of cancer probability for PCDD/PCDF [42] **-1**
Environmental impact	a) Favourable impact [74] **+1**

7.4.6. Animal/bone meal, specified risk material

Resource consumption / conservation	a) Reduction of coal use [22,35,63] **+1,4**
Global Warming	a) CO_2 emissions are climate neutral [2,20,21,33] **+1,6** b) Reduction of CO_2 emissions [22,23,35] **+1,4** c) Effective way to reduce GHG [12] **+1**
CACs/Non hazardous air pollutant	a) NOx can be converted into neutral molecular nitrose by the minerals of cement [63] **+1**
Metals & HAPs	a) No impact on PCDD/PCDF [62] **0**
Operations Waste	a) Tallow is used in soap manufacturing [22] **+1** b) No waste from storage and handling [23] **+1** c) Slight increase of dust [23] **-1** d) Safe and environmentally sound solution for destruction of contaminated animals [1,2,34] **+1,4** e) Decrease demand for landfill [22,23] **+1,2**
Other Social Impact	a) No detrimental impact on human health [35] **+1**
Environmental impact	a) No change for overall emissions [22,35] **0** b) No change in emissions to water [22,35] **0** c) No change in emissions to land [22,35] **0**

7.4.7. Waste wood (sawdust, paper fractions)

Resource consumption / conservation	a) Inorganic ash used as raw material for the clinker [26] **+1** b) Reduction of use of fossil fuel [48] **+1**
Global Warming	a) CO_2 emissions are climate neutral [2,20,21,26,33,38,48,75] **+2,4** b) CO_2 reduction depends on transportation [48] **0** c) Effective way to reduce GHG [12,26] **+1,2**
CACs/Non hazardous air pollutant	
Metals & HAPs	a) Volatile and semi-volatile metals are an issue if not limited at the source [8] **0**
Operations Waste	a) No additional waste [26] **+1** b) No waste from storage and handling [26] **+1** c) Unlike change of dust quantities, composition may change [26] **0** d) Decrease demand for landfill [26,38] **+1,2**
Other Social Impact	a) Unchanged cancer risk [26] **0** b) Insignificant potential impact [26] **0**
Environmental impact	a) No change in emissions to air [26] **0** b) No change in emissions to water [26] **0** c) No change in emissions to land [26] **0** d) Favourable impact [74] **+1**

7.4.8.Used Tires

Resource consumption / conservation	a) Reduction of coal use [35] **+1** b) Reduction of mined material [8,38] **+1,2**
Global Warming	a) Reduction of CO_2 emissions [2,12,14,55] **+1,6**
CACs/Non hazardous air pollutant	a) Decrease of NO_x [7,10,12,35,38,64] **+1,8** b) Non statistically significant reduction of NO_x [14,15] **0** c) Increase of NO_x [50] **-1** d) Decrease of SO_2 [7,12] **+1,2** e) Non statistically significant reduction of SO_2 [14,15] **0** f) Increase of SO_2 [7,50,64] **-1,4** g) Decrease of particulate [7] **+1** h) Increase of particulate [7,64] **-1,2** i) Tire chips: No statistically significant change in overall emissions compared to other fuel mix with coal and Cemfuel [7] **0** j) Increase of CO [7,50,64] **-1,4** k) Non statistically significant increase of CO [14,15] **0** l) Non statistically significant change in particulate emissions [14,15] **0**
Metals & HAPs	a) Increase of VOC [7,39] **-1,2** b) Increase of Zn emissions [7,64] **-1,2** c) No evidence for increase/decrease of PCDD [7,50,62] **0** d) Non statistically significant evidence for increase/decrease of metals [7,14,15] **0** e) Decrease of PCDD/PCDF emissions [14,15,64] **+2,8** f) Increase of PCDD/PCDF emissions [39] **-1** g) Non statistically significant increase of hydrocarbon emissions [14,15] **0** h) HCl under <u>limits</u> [39] **0** i) HF under <u>limits</u> [39] **0** j) Increase of HCl [64] **-1** k) Increase of metals but Hg [39,64] **-1,2** l) Dust emissions not affected [50] **0** m) Decrease of Hg [51] **+1**
Operations Waste	a) Iron in tires replace expensive additives [7,12,14,38] **+1,6** b) Heavy metals residues are locked into the clinker [8,12] **+1,2** c) Use in cement kilns provides the best or the second best waste management option for 7 out 10 impact categories [7] **+1** d) Avoid eyesore [14] **+1** e) Avoid uncontrolled burning [14] **+1** f) Complete destruction in the kiln [14,15,34] **+1,4** g) Avoid landfilling [15,21,34,35,38] **+1,8** h) Avoid mosquitoes proliferation [34] **+1**
Other Social Impact	a) Reduce health concerns [38] **+1** b) Issue with public perception [38,55] **-1,2** c) No serious health impact [55] **+1**
Environmental impact	a) Reduction of total impact of emissions to air [7,14,15,34,35] **+1,8**

7.4.9. Biomass (e.g., rice husk, palm kernel shells, algae, cottonseed oil, coffee bean husk)

Resource consumption / conservation	a) Reduction of use of fossil fuels [25,29,31,32,35] **+1,8**
Global Warming	a) CO2 emissions are climate neutral [2,20,21,31,32,33,35,72] **+2,4** b) Effective way to reduce GHG [12,29,35] **+1,4**
CACs/Non hazardous air pollutant	a) Low SO2 emissions [72] **+1**
Metals & HAPs	a) Low PCDD/PCDF emissions [72] **+2** b) Very low heavy metal emissions [72] **+1**
Operations Waste	a) Closing the loop [29,35] **+1,2** b) Decrease demand for landfill/incineration [35] **+1**
Other Social Impact	a) Source of income for local communities [29,31,32,34] **+1.6**
Environmental impact	a) Local biomass reduces transport impact [35] **+1** b) Help to evacuate flood water [37] **+1** c) Reduced environmental impact [72] **+1**

7.4.10. Hazardous Waste

Resource consumption / conservation	a) Reduction of use of fossil fuels [18,21,70] **+1,4**
Global Warming	a) Reduction of CO2 emissions [18,21] **+1,2**
CACs/Non hazardous air pollutant	
Metals & HAPs	a) HCl emissions [21] **0** b) Decrease of chlorinated organic compounds [70] **+1** c) No impact on PCDD/PCDF [40,57] **0** d) Increase in Ni, Cr, Sb, Pb [46] **-4** e) Decrease in As, Be, Cd, Hg, Ar, Tl [46] **+6** f) Decrease in Cr, Cu, Zn [66] **+3** g) Increased metal concentrations [67] **-1** h) PCDD/PCDF increased with liquid hazardous waste [70] **-2**
Operations Waste	
Other Social Impact	
Environmental impact	a) No change in emissions to air [18] **0** b) Co-processing could be part of the solution for the final treatment [28] **0**

7.5. Findings Tables with Values for Economic and Technical Impact for RQ1

7.5.1. General alternative fuel

Economic Impact	a) Co-processing is not always the most economic way of using waste, case-by-case assessment [1,28] **0** b) Costs vary with the type of waste and local conditions [1] **0** c) Alternative fuel costs are likely to increase with high CO2 costs, this could create sourcing at acceptable prices issues [12] **0** d) Save money [28,38] **+1,2** e) Energy recovery results in net energy savings [13] **+1**
Use in cement kiln/process	a) Sometimes is required pre-processing/ pre-treatment [1,2,12,28,38] **0** b) Not all the cement kilns are suitable for alternative fuel, modification are required [1,7,38] **0** c) Additional environmental equipment may be required [1,16,19,21] **0** d) Special control and process measures required for safety standards [1,11,28] **-1,4** e) Selection of feed points relative to alternative fuels [1,8,28] **0** f) Need to ensure feed rate [1,28] **0** g) Waste fuels should not use during start-up and shut-down of kilns [1] **-1** h) Process and quality are sensitive to components such as chloride, sulphur, alkalis and P2O5 [7,15,21,28] **0** i) Increase of energy efficiency [13] **+1** j) Ensure traceability [28] **-1** k) Raw materials should be chosen according to the particular alternative fuel [28] **0** l) Need of performance tests [38] **-1** m) Handling systems are fuel specific [38] **0** n) Need for permit [38] **0**
Availability	a) Local waste collection networks must be adequate [12,21,38] **0** b) Waste management legislation affects alternative fuels availability [12] **-1** c) Influenced by types of local industry [12,38] **0** d) Influenced by level of development [12] **0** e) Influenced by local environment awareness [12] **0** f) Availability is often a key barrier to higher substitution rates [12] **0** g) Growing commercial market for brokers [38] **+1** h) Engineered fuel is homogenous [38] **+1**

7.5.2. Municipal and commercial waste, PASr, PASi waste, RDF, WDF

Economic Impact	a) Reduction in purchased fuel cost [7] **+1** b) Profuel: 50% carbon neutral in EU/ETS [20] **0** c) Reduction in energy for coal grinding [7,24] **+1,2** d) Minimize landfilling costs [30,53] **+1,2** e) Cost of RDF per heat unit is higher than coal and coke [44] **-1** f) Increased economic return [52,59] **+1,2** g) Energy cost saving [53] **+1** h) Low cost of RDF [44] **+1** i) RDF has low calorific value [44] **-1**
Use in cement kiln/process	a) Risk of fire [1] **0** b) They must be treated before using [2] **-1** c) They must be sorted [8,28] **-1,2** d) Need to build-up technical know-how and experience on how to use waste-derived fuels without jeopardizing process and product quality [6] **-1** e) Limited availability [6] **-1** f) MSW is not a suitable fuel due to its high variability and moisture content [7] **-1** g) RDF is a suitable fuel [7] **+1** h) RDF: Reduce clinker sulphate content to a more grindable cement [7] **+1** i) Need of a bypass system for chloride removal [7] **-1** j) Plastics should be separately sorted [38] **-1**
Availability	a) SRF: Great flexibility to secure and manage the supply of fuel [24] **+1** b) Advantage of territorial distribution [44] **+1**

7.5.3. Industrial, commercial and institutional residues

Economic Impact	a) Solvent liquid fuels is less economically attractive due to the kiln output reduction [5] **0** b) Economic impact of solvent liquid fuel is site specific [5] **0** c) ASR, SC: Energy content similar to coal [38] **0** d) CSOS: Lower energy content than coal [38] **-1** e) SC separation need labour [38] **-1** f) Energy costs saving due to the better grindability of clinker with lower sulphur content [5] **+1**
Use in cement kiln/process	a) Risk of fire, explosion and spills for solvents [1] **0** b) Solvent liquid fuels with high moisture content can decrease the kiln output [5,7] **-1,2** c) No additional pollution control measures are required for solvent liquid fuels [5] **0** d) Pre-treatment needed [35,38,54] **-1,4** e) ASR: Need for technological upgrade [38] **-1** f) ASR: Need for additional pollution control [38] **-1** g) CSOS: Need for permits [38] **0** h) SC: Loose material [38] **-1** i) Reduction of combustion temperature for emulsions [45] **-1** j) Reduction of NOx if oil emulsions are substituted by water [45] **0** k) Except PVC backed carpet, all carpets are suitable for kilns [49] **+1** l) Carpet grinding can increase NOx emissions [49] **-1**
Availability	a) ASR, SC: High availability [38,54] **+2** b) CSOS: Not continuous supply [38] **-1** c) SC: Need to consolidate quantities from small generators [38] **0** d) Widely distributed cement kilns facilitates the collection and reduces transportation costs of waste carpet in USA [49] **0**

7.5.4. Plastics

Economic Impact	a) Plastic suppliers must be paid [8] **-1** b) Low capital and maintenance costs [35] **+1** c) Energy content comparable with coal [8,38] **0**
Use in cement kiln/process	a) No odours [8] **0** b) Chlorine is detrimental for operations [35,38] **-1,2** c) Additional pollution control devices are required [38] **-1** d) Quality of material is an issue [8,38] **-1,2**
Availability	a) Difficult to achieve consistent quantities of materials [38] **-1** b) Competition with recyclers (higher waste hierarchy) [38] **-1** c) Waste stream needs to be separated [38] **-1** d) Supply/logistics barriers [38] **-1**

7.5.5. Sewage Sludge

Economic Impact	a) Special silos are required [8] **-1** b) Carbon neutral in EU/ETS [19] **0** c) Minimize landfilling costs [30] **+1** d) Lower energy content than coal [38] **-1** e) Increased economic return thanks to CO_2 reduction and reduced cancer risk [58] **+2** f) Increased economic return [61] **+1**
Use in cement kiln/process	a) Sludge storing requires dehumidification to avoid self-heating [8] **-1** b) Additional pollution control devices are required [38] **-1** c) Drying required [38] **-1** d) Existing infrastructure is largely based on land application [38] **-1** e) Need to consider pathogens [38] **-1** f) Handling issues [38] **-1**
Availability	a) Largely available [38] **+1**

7.5.6. Animal/bone meal, specified risk material

Economic Impact	a) 100% Carbon neutral in EU/ETS [19,20] **0** b) Reduction in energy for coal grinding [23] **+1**
Use in cement kiln/process	a) Risk of fire/explosion [1] **0** b) Cleaning and disinfection of storage areas is very important [8] **-1** c) No impact on cement quality [63] **0**
Availability	a) Can trigger unexpected shutdown [30] **-1**

7.5.7. Waste wood (sawdust, paper fractions)

Economic Impact	a) Paper suppliers must be paid [8] **-1** b) Carbon neutral in EU/ETS [19] **0** c) Reduction in energy for coal grinding [26] **+1** d) Paper has lower energy content than coal [8,38] **-1,2** e) Economic convenience is strongly dependent on the incentives given for per unit CO2 reduction [48] **0**
Use in cement kiln/process	a) Risk of fire/explosion [1,38] **0** b) Feasibility of processing materials [38] **+1** c) Need for additional equipment [38] **-1** d) Equipment needed to keep sawdust dry [38] **-1** e) Paper must be dried [8] **-1**
Availability	a) Flexibility to switch to other fuels required [26] **0** b) Available [38,48] **+1,2** c) Need to consolidate quantities [38] **0** d) Competition with other markets (higher waste hierarchy) [38,48] **-1,2** e) Difficult to sustain economic supply [38] **-1** f) Supply uncertainty can be a problem [48] **-1**

7.5.8. Used Tires

Economic Impact	a) Higher energy content than coal [5,12,14,15,38] **+1,8** b) More competitive plants due to the savings on coal [35] **+1**
Use in cement kiln/process	a) Risk of fire [1,8] **0** b) Proliferation of mosquitoes [1] **-1** c) Storage must be carefully studied and it is different fro whole and shredded tires [8] **0** d) Need of pre-treatment according to the kiln [8] **0** e) Homogeneous material [34] **+1** f) Not all the cement kilns are able to process whole tires, chipped tires are more expensive [38] **0**
Availability	a) Increasing competition for scrap tires [38] **-1** b) Good availability [38] **+1**

7.5.9. Biomass (e.g., rice husk, palm kernel shells, algae, cottonseed oil, coffee bean husk)

Economic Impact	a) Carbon neutral in EU/ETS [19] **0** b) Reduction of fuel costs [32] **+1** c) Give value to little value fields [37] +1
Use in cement kiln/process	a) It is expected a loss of production of 5-7% due to gas flow [7] **-1** b) Additional equipment may be required [35] **0**
Availability	a) Need for agricultural residues [30] **0** b) Can trigger unexpected shutdown [30] **-1** c) Possible supply issues with agricultural by-products [38] **-1**

7.5.10. Hazardous waste

Economic Impact	
Use in cement kiln/process	a) No change in manufacturing process [18] **0** b) No change in quality [18] **0** c) Quick cooling in air pollution control device reduces all emissions[40,57] **+1,2** d) Differences in removal efficiency between dry and wet processes [66] **0**
Availability	a) Slow but steady availability decline [38] **-1**

7.6. Findings Tables with Values for Municipal Solid Waste for RQ2

7.6.1. Recycling

Resource consumption / conservation	a. Supply raw materials to industries [21] **+1**
Global Warming	a. Lowering GHG respect to landfilling [17,21,22] **+1,4** b. CO2 savings respect to landfilling [17] **+1**
CACs/Non hazardous air pollutant	
Metals & HAPs	a. Emission of dust [16] **-1**
Operations Waste	a. Waste water [16] **-1** b. Final residues [16] **-1**
Economic Impacts	
Health and social impact	a. Noise [16] **-1** b. Creation of jobs and income [21,22] **+1,2** c. Reduce landfills [21,22] **+1,2**
Technical feasibility	

7.6.2. Recycling (Composting)

Resource consumption / conservation	a. Some organic materials are rich in nutrients [21] **+1**
Global Warming	a. Emission of CH4 [16] **-1** b. Emission of CO2 [16] **-1** c. Lowering GHG respect to landfilling [17,21,22] **+1,4** d. CO2 savings respect to landfilling [17] **+1**
CACs/Non hazardous air pollutant	
Metals & HAPs	
Operations Waste	a. Toxic substances in the food chain [16] **-1**
Economic Impacts	
Health and social impact	a. Creation of jobs and income [21,22] **+1,2** b. Reduce landfills [21,22] **+1,2** c. Advantages for local farmers [22] **+1**
Technical feasibility	a. A minimum amount of waste is required to make the process cost effective [22] **0**

7.6.3. Energy Recovery in Cement Mfg.

Resource consumption / conservation	a. Electricity generation/heat availability reduced [1] **-1** b. Higher electricity consumption than incineration due to composting process [34] **-1**
Global Warming	a. Reduction of GHG [1] **+1** b. Optimal scenario [1] **+1** c. Better results than incineration [30,34] **+1,2**
CACs/Non hazardous air pollutant	a. Reduction of SO2 emission potential, higher than in coal fired plant [1] +**1** b. Slight increase of SOx potential [1] **-1**
Metals & HAPs	a. Gas emissions within limits [1] **0** b. Emission of micropollutants [6] **-1** c. Formation of PCDD [6] **-1** d. Transfer of substance in waste to the cement or air [6] **0**
Operations Waste	a. Slight increase of ashes [1] **-1** b. Total disposal process (ashes taken up in the cement) [5] **+1** c. Inert material is suitable for landfill [5] **+1**
Economic Impacts	a. Not necessary dry and pelletize RDF before use [5] **+1** b. Economic impact highly dependent on taxes on incineration, incentives for renewable energy, plant logistical position, standards required for emissions (needs of treatments) [6] **0** c. Cost reduction for waste treatment [34] **+1**
Health and social impact	
Technical feasibility	a. Minimum risk to fuel users [1] **+1** b. The best option due to the low technological risks, environmental emissions and fuel cost [1] **+1** c. The type of processing involved is quite familiar to technical people and operators accustomed to cement production [5] **+1** d. MSW quality is critical [5] **0** e. Efficient waste gas treatment plant is necessary [5] **-1** f. the presence of certain minor metallic elements limits the amount of refuse ash that cement clinker can take up without affecting the quality of the final cement [5] **-1** g. On burning RDF →build-up of recirculating volatiles (metalhalide salts), which can lead to a build-up f deposits in the kiln and preheater, and of chlorides in the cement. To alleviate these potential problems, a bypass can be fitted [5] **0** h. Necessity of political agreements [6] **-1**

7.6.4. Incineration

Resource consumption / conservation	
Global Warming	a. Emission of CO_2 [16] **-1** b. Lowering GHG respect to landfilling [17] **+1** c. CO_2 savings respect to landfilling [17] **+1**
CACs/Non hazardous air pollutant	a. Limited formation of NO_x in fluidised bed [6] +**1** b. Emission of SO_2, NO_x, CO [16] **-3**
Metals & HAPs	a. Production of toxin and heavy metals [16] **-1** b. Emission of HCl, HF, NMVOC, N_2O, PCDD, PCDF, metals [16] **-7** c. Better balance of Hg toxicity parameter than cogeneration [30] **+1** d. Fine dust toxicity comparable to cogeneration [30] **0**
Operations Waste	a. Possible atmospheric flows or residuals from fumes treatment [6] **-1** b. Slag, fly ashes and scrap [16] **-1** c. Toxic substances in the food chain [16] **-1** d. 90% reduction of waste volumes [21] **+1**
Economic Impacts	a. Facility construction is expensive [21] **-1**
Health and social impact	a. Hazardous substances on surface water [16] **-1** b. Eutrophication comparable to cogeneration [30] **0** c. Acidification comparable to cogeneration [30] **0**
Technical feasibility	

7.6.5. Incineration w/ Elec. Generation

Resource consumption / conservation	a. Substitution of fossil fuels [21] **+1**
Global Warming	a. Emission of CO_2 [16] **-1** b. Lowering GHG respect to landfilling [17] **+1** c. CO_2 savings respect to landfilling [17] **+1**
CACs/Non hazardous air pollutant	a. Emission of SO_2, NO_x, CO [16] **-3**
Metals & HAPs	a. Production of toxin and heavy metals that may leach in the water supply [5,16] **-1,2** b. Emission of HCl, HF, NMVOC, N_2O, PCDD, PCDF, metals [16] **-7**
Operations Waste	a. Residual biologically inert [5] **+1** b. Slag, fly ashes and scrap [16] **-1** c. Toxic substances in the food chain [16] **-1** d. 85-90% reduction of waste volumes [5,21] **+1,2**
Economic Impacts	a. Net treatment costs with incineration are often no greater than those for controlled landfill [5] **+1** b. Facility construction is expensive [5,21] **-1,2**
Health and social impact	a. Hazardous substances on surface water [16] **-1**
Technical feasibility	a. Incinerators require qualified and trained technical staff to operate and maintain them [5] **-1** b. Does not require the plant to be located adjacent to the potential user. [5] **+1** c. One constraint common to all incineration projects is the need to feed the facility with MSW of a certain minimum quality. In order to be suitable for combustion without supplementary fuel [5] **0**

7.6.6. Incineration w/ Heat Generation

Resource consumption / conservation	a. Substitution of fossil fuels [21] **+1**
Global Warming	a. Emission of CO_2 [16] **-1** b. Lowering GHG respect to landfilling [17] **+1** c. CO_2 savings respect to landfilling [17] **+1**
CACs/Non hazardous air pollutant	a. Increase of SO_2 emission [1] **-1** b. Reduction of SO_x potential [6] **+1** c. Emission of SO_2, NO_x, CO [16] **-3**
Metals & HAPs	a. Production of toxin and heavy metals that may leach in the water supply [5,16] **-1,2** b. Emission of HCl, HF, NMVOC, N_2O, PCDD, PCDF, metals [16] **-7**
Operations Waste	a. Residual biologically inert [5] **+1** b. Slag, fly ashes and scrap [16] **-1** c. Toxic substances in the food chain [16] **-1** d. 85-90% reduction of waste volumes [5,21] **+1,2**
Economic Impacts	a. Net treatment costs with incineration are often no greater than those for controlled landfill [5] **+1** b. Facility construction is expensive [5,21] **-1,2**
Health and social impact	a. Hazardous substances on surface water [16] **-1**
Technical feasibility	a. Incinerators require qualified and trained technical staff to operate and maintain them [5] **-1** b. Does not require the plant to be located adjacent to the potential user. [5] **+1** c. One constraint common to all incineration projects is the need to feed the facility with MSW of a certain minimum quality. In order to be suitable for combustion without supplementary fuel [5] **0**

7.6.7. Incineration w/ Electricity and Heat Generation

Resource consumption / conservation	a. Electricity generation/heat availability increased [1] **+1** b. Substitution of fossil fuels [21] **+1**
Global Warming	a. Increase of GHG [1] **-1** b. Emission of CO_2 [16] **-1** c. Lowering GHG respect to landfilling [17] **+1** d. CO_2 savings respect to landfilling [17] **+1**
CACs/Non hazardous air pollutant	a. Reduction of SO_2 emission potential [1] **+1** b. Large reduction of SO_x potential [1] **+1** c. Emission of SO_2, NO_x, CO [16] **-3**
Metals & HAPs	a. Gas emissions above limits [1] **0** b. Production of toxin and heavy metals that may leach in the water supply [5,16] **-1,2** c. Emission of HCl, HF, NMVOC, N_2O, PCDD, PCDF, metals [16] **-7**
Operations Waste	a. Large reduction of ashes [1] **+1** b. Residual biologically inert [5] **+1** c. Slag, fly ashes and scrap [16] **-1** d. Toxic substances in the food chain [16] **-1** e. 85-90% reduction of waste volumes [5,21] **+1,2**
Economic Impacts	a. Net treatment costs with incineration are often no greater than those for controlled landfill [5] **+1** b. Facility construction is expensive [5,21] **-1,2** c. Combined heat and power facilities will give the most economic operation [5] **+1**
Health and social impact	a. Hazardous substances on surface water [16] **-1**
Technical feasibility	a. Incinerators require qualified and trained technical staff to operate and maintain them [5] **-1** b. Does not require the plant to be located adjacent to the potential user. [5] **+1** c. One constraint common to all incineration projects is the need to feed the facility with MSW of a certain minimum quality. In order to be suitable for combustion without supplementary fuel [5] **0**

7.6.8. Landfill

Resource consumption / conservation	a. Increasingly full [16] **-1**
Global Warming	a. Emission of CH_4 [16] **-1** b. Emission of CO_2 [16] **-1**
CACs/Non hazardous air pollutant	
Metals & HAPs	a. Metals and toxins leaking to groundwater and soil [16] **-1**
Operations Waste	a. Explosive and toxic gas generated [16] **-1** b. Salts [16] **-1** c. Properly constructed and managed landfills can be used to recover CH_4 [21] **+1**
Economic Impacts	
Health and social impact	a. Emission of odours [16] **-1** b. Hazardous substances on soil [16] **-1**
Technical feasibility	

7.6.9. Production of densified refuse derived fuel (d-RDF) in pellet form

Resource consumption / conservation	
Global Warming	
CACs/Non hazardous air pollutant	
Metals & HAPs	a. The need for environmental control is transferred downstream to the end-user, who may not be equipped to handle it [5] **-1**
Operations Waste	
Economic Impacts	
Health and social impact	
Technical feasibility	

7.6.10. Coal-fired power plant

Resource consumption / conservation	a. Electricity generation/heat availability is reduced [1] **-1**
Global Warming	a. Second optimal scenario [1] **+1** b. Reduction of GHG emissions [1] **+1** c. Better results than incineration [30] **+1**
CACs/Non hazardous air pollutant	a. Reduction of SO2 emission potential [1] **+1** b. Increase of SOx potential [1] **-1**
Metals & HAPs	a. Gas emissions within limits [1] **0**
Operations Waste	a. Potential increase of ashes [1] **-1**
Economic Impacts	a. Total revenues appear to be the highest from the four scenarios considered in the document [1] **+1**
Health and social impact	
Technical feasibility	a. It is unproven. The major concerns may be with the existing uncertain regulatory climate for waste derived fuel, difficulty in raising the finance and lack of market maturity. It is undecided whether SRF is legally a fuel or waste This uncertainty will lead to the difficulties in raising project finance [1] **-1**

7.6.11. Biomass combustion system using woodchips (heat and electricity)

Resource consumption / conservation	a. Electricity generation/heat availability is reduced [1] **-1**
Global Warming	a. Higher GHG than incineration [1] **-1**
CACs/Non hazardous air pollutant	a. Increase of SO2 emission potential [1] **-1** b. Increase of SOx potential [1] **-1**
Metals & HAPs	a. Gas emissions within limits [1] **0**
Operations Waste	a. Potential increase of ashes [1] **-1**
Economic Impacts	
Health and social impact	
Technical feasibility	a. Electricity generation/heat availability is reduced when using SRF as co-fuel [1] **-1**

7.7. Findings Table with Values for Sewage and Wastewater Sludge for RQ2

7.7.1. Composting

Resource consumption / conservation	a. Best way for disposal [18] **+1** b. Utilization of nutrients [18,23] **+1,2** c. Improvement of the humus layer of the soil [18,23] **+1,2** d. Aeration requires energy [18] **-1**
Global Warming	
CACs/Non hazardous air pollutant	
Metals & HAPs	
Operations Waste	a. Less concentration than disposal avoids soil contamination [23] **+1**
Economic Impacts	a. Reduction of the volume of material respect to non composting [18] **+1** b. Storage facilitation respect to non composting [18] **+1** c. Higher treatment costs respect to non composting [18] **-1**
Health and social impact	a. Shortening of tree growing in forests [23] **+1** b. Control soil erosion [23] **+1** c. Offensive odours [23] **-1**
Technical feasibility	a. Need to mix sludge with a bulking agent : waste (cheaper) or bought agent [18] **-1**

7.7.2. Recycling (agricultural use not composted)

Resource consumption / conservation	a. Best way for disposal [18] **+1** b. Utilization of nutrients [18,23] **+1,2** c. Improvement of the humus layer of the soil [18,23] **+1,2** d. Lowest non-renewable energy consumption [31] **+1**
Global Warming	a. Equivalent to pyrolysis [31] **0**
CACs/Non hazardous air pollutant	
Metals & HAPs	a. Many heavy metal can be released [2,31] **-1,2**
Operations Waste	a. Less concentration than disposal avoids soil contamination [23] **+1**
Economic Impacts	a. Cheapest disposal route [18] **+1** b. Investment in storage facilities [18] **0**
Health and social impact	a. Metals may enter in the human food chain [2] **-1** b. Lack of knowledge about micro pollutant and pathogenic organisms and their impact on food chain [18] **0** c. Shortening of tree growing in forests [23] **+1** d. Control soil erosion [23] **+1** e. Offensive odours [23] **-1**
Technical feasibility	

7.7.3. Energy Recovery in Cement Mfg.

Resource consumption / conservation	a. Worst way for disposal[18] **-1** b. Energetic valorization [18] **+1**
Global Warming	a. Minimal emission of CH4 and N2O [2] **+2** b. Best disposal method [31] **+1**
CACs/Non hazardous air pollutant	
Metals & HAPs	a. Emission of harmful substances with heavy metals and dust [2] **-1** b. Pollutants stabilized in the clinker [18] **+1**
Operations Waste	a. Ash incorporated in the clinker [35] **+1**
Economic Impacts	a. Justified for sludge not allowed to be used in agriculture or incinerated in MSW incineration [18] **0** b. Capital intensive [18] **-1** c. Advantage of existing infrastructure [35] **+1** d. No added cost of sludge handling [35] **+1**
Health and social impact	a. Minimization of odours [18] **+1**
Technical feasibility	a. Reliable system [18] **+1** b. Low sensitivity to composition [18] **+1**

7.7.4. Incineration

Resource consumption / conservation	a. Worst way for disposal [18] **-1** b. Lowest non-renewable energy consumption [31] **+1**
Global Warming	a. Restricted balance [31] **0**
CACs/Non hazardous air pollutant	
Metals & HAPs	a. Release of heavy metals [2] **-1** b. Emission of PCDD,PCDF, NOx, N2O, SO2, HCl, HF and CxHy [2] **-8** c. Destruction of volatile solid pathogens and degradation of toxic organic chemicals [23] **+2** d. PCDD may be formed [23] **0** e. Metals are concentrated in the ash [23] **+1** f. Particulate matter included in exhaust gases [23] **-1**
Operations Waste	a. Solid residues [2] **-1** b. Reduction to 20% of initial mass (in ash) [23] +**1** c. Valuable by-products [23] **+1**
Economic Impacts	a. Capital intensive [18] **-1**
Health and social impact	a. Handling of solid residues is a concern [2] **-1** b. Minimization of odours [18] **+1** c. Other biosolids disposal options more acceptable by the communities or cheaper [23] **-1**
Technical feasibility	a. Reliable system [18] **+1** b. Low sensitivity to composition [18] **+1**

7.7.5. Incineration w/ Elec. Generation

Resource consumption / conservation	a. Worst way for disposal [18] **-1** b. Energetic valorization [18] **+1** c. Lowest non-renewable energy consumption [31] **+1**
Global Warming	a. Restricted balance [31] **0**
CACs/Non hazardous air pollutant	
Metals & HAPs	a. Emission of air pollutant [4] **-1** b. Destruction of volatile solid pathogens and degradation of toxic organic chemicals [23] **+2** c. PCDD may be formed [23] **0** d. Metals are concentrated in the ash [4,23] **+1,2** e. Particulate matter included in exhaust gases [23] **-1**
Operations Waste	a. Ash has to be disposed of or can be used as a source for the production of building materials [4] **+1** b. Reduction to 20% of initial mass (in ash) [23] **+1** c. Valuable by-products [23] **+1**
Economic Impacts	a. Large quantities of polluted exhaust gases → the costs of an efficient and adequate gas treatment system are very high [4] **-1** b. Capital intensive [18] **-1**
Health and social impact	a. Minimization of odours [18] **+1** b. Other biosolids disposal options more acceptable by the communities or cheaper [23] **-1**
Technical feasibility	a. Reliable system [18] **+1** b. Low sensitivity to composition [18] **+1**

7.7.6. Landfill

Resource consumption / conservation	
Global Warming	a. Worst disposal method [31] **-1**
CACs/Non hazardous air pollutant	
Metals & HAPs	
Operations Waste	
Economic Impacts	a. Costs are increasing generally [23] **-1**
Health and social impact	
Technical feasibility	

7.7.7. Anaerobic digestion

Resource consumption / conservation	a. Nitrogen and phosphorous nutrients can be used as fertilizers [2] **+1** b. Biogas can be used as an energy source for the production of electricity and/or heat and/or as fuel [2,4,31] **+1,4** c. The moisture is not converted to vapour, saving energy respect to combustion [2] **+1** d. Energy balance can be roughly compared to WtCHP [2] **0** e. Reduction of organic matter [31] **+1** f. Most preferable treatment option [35] **+1**
Global Warming	
CACs/Non hazardous air pollutant	
Metals & HAPs	a. Residual toxic organics, heavy metals, soluble phosphates, and inorganic [4] **-4**
Operations Waste	
Economic Impacts	
Health and social impact	a. Create jobs [20] **+1**
Technical feasibility	

7.7.9. Production of biofuel

Resource consumption / conservation	
Global Warming	
CACs/Non hazardous air pollutant	
Metals & HAPs	
Operations Waste	
Economic Impacts	a. Research not very promising [4] **-1**
Health and social impact	
Technical feasibility	

7.7.10. Direct production of electricity from sewage sludge in microbial fuel cells

Resource consumption / conservation	
Global Warming	
CACs/Non hazardous air pollutant	
Metals & HAPs	a. Sludge contains toxic organics and a substantial amount of non-toxic inorganic. A further post-treatment of the residual waste stream will be necessary [4] **-4**
Operations Waste	
Economic Impacts	
Health and social impact	
Technical feasibility	

7.7.11. Co-incineration of sewage sludge in coal-fired power plants

Resource consumption / conservation	
Global Warming	
CACs/Non hazardous air pollutant	
Metals & HAPs	a. The effect of the incineration of the sludge on the air and ash qualities can be neglected [4] **0**
Operations Waste	
Economic Impacts	
Health and social impact	
Technical feasibility	

7.7.12. Gasification

Resource consumption / conservation	a. Converts the sewage sludge into a useable fuel [2] **+1** b. The total process is actually energetically self-sustaining and no energy input is necessary [2] **+1**
Global Warming	
CACs/Non hazardous air pollutant	
Metals & HAPs	a. Compared to incineration can prevent problems as the need for supplemental fuel, emissions of sulphur oxides, nitrogen oxides, heavy metals and fly ash and the potential production of chlorinated dibezodioxins and dibenzofurans [2] **+5**
Operations Waste	
Economic Impacts	a. The treatment process of the gases can be more complicated than incineration [4] **-1**
Health and social impact	
Technical feasibility	a. Process performance much more complicated than incineration [4] **-1** b. Valuable gases can be produced as basic chemicals or as fuel (better compared to incineration) [4] **+1** c. Conversion of the combustible gases of both systems into electrical power can be achieved more efficiently than incineration [4] **+1**

7.7.13. Pyrolysis

Resource consumption / conservation	a. Pyrolysis gas can be used as fuel, as well as the char, while pyrolytic oil can be used as raw material for chemical industries, even as fuel [2] **+1**
Global Warming	a. CH_4, CO, CO_2 emissions [2] **-3** b. Equivalent to agricultural spreading [31] **0**
CACs/Non hazardous air pollutant	a. H_2 emissions [2] **-1**
Metals & HAPs	a. Less pollutant than incineration and combustion [2] **0**
Operations Waste	a. Solid fraction consists mainly of char [2] **+1** b. Liquid fraction consists mainly of tar and oil (acetic acid, acetone and methanol) [2] **+1**
Economic Impacts	a. The treatment process of the gases can be more complicated than incineration [4] **-1**
Health and social impact	
Technical feasibility	a. Process performance much more complicated than incineration [4] **0** b. Valuable gases can be produced as basic chemicals or as fuel (better compared to incineration) [4] **+1** c. Conversion of the combustible gases of both systems into electrical power can be achieved more efficiently than incineration [4] **+1**

7.7.14. Wet oxidation

Resource consumption / conservation	
Global Warming	a. Emission of CO_2 [2] **-1**
CACs/Non hazardous air pollutant	a. Emissions of nitrogen [2] **-1**
Metals & HAPs	a. Toxic organic compounds are completely oxidized [4] **+1**
Operations Waste	a. Water resulting from the process [2] **-1**
Economic Impacts	a. Advantage that off gas treatment is very simple in comparison to incineration [4] **+1**
Health and social impact	
Technical feasibility	a. Large-scale practical experience is not available yet [4] **-1** b. Use of oxygen in the process, use of high-pressure piping, the need of high-pressure reactors, and potential corrosion problems if chlorides are present in the sludge might be bottlenecks in the acceptance and further development of this technology [4] **-1**

7.7.15. Hydrothermal processes

Resource consumption / conservation	a. Recovering of volatile fatty acids, phosphorous compounds, organic compounds for enhanced anaerobic biogas production, and coagulants [4] **+1** b. Volatile fatty acids and other dissolved biodegradable organic compounds can be beneficially used as an energy or organic carbon source in the denitrification step of the wastewater treatment process and in the anaerobic digestion step [4] **+1**
Global Warming	
CACs/Non hazardous air pollutant	
Metals & HAPs	a. It is not clear what happens to the toxics, especially the toxic organics [4] **0**
Operations Waste	
Economic Impacts	
Health and social impact	
Technical feasibility	a. Post-treatment is necessary [4] **-1**

7.7.16. Raw material in cement production

Resource consumption / conservation	a. Either ash or dried sludge can be used [4] **+1**
Global Warming	
CACs/Non hazardous air pollutant	
Metals & HAPs	a. Toxic organic pollutants in the sludge are completely oxidized, and because of the high process temperature, heavy metals are immobilized in the cement. [4] **+2**
Operations Waste	
Economic Impacts	a. Costs of thermal solidification are high [4] **-1**
Health and social impact	
Technical feasibility	

7.7.17. Heat only plants

Resource consumption / conservation	
Global Warming	
CACs/Non hazardous air pollutant	
Metals & HAPs	
Operations Waste	
Economic Impacts	a. Lower payback period than cogeneration plants [3] **-1**
Health and social impact	
Technical feasibility	

7.7.18. Cogeneration plants (WtCHP)

Resource consumption / conservation	
Global Warming	
CACs/Non hazardous air pollutant	
Metals & HAPs	
Operations Waste	
Economic Impacts	a. Competitive respect to other combustion technologies if: – There is no cement kiln within a rational distance of the wastewater treatment plant. – The distance to the co-combustion furnaces is too long – The possibility for phosphorous recovery is considered to be worth the separate investment [3] **0**
Health and social impact	
Technical feasibility	

7.8. Findings Table with Values for Plastics for RQ2

	Resource Consumption / Conservation	Global Warming	CACs / Non-hazardous Air Pollutants	Metals & HAPs	Operations Waste	Economic Impacts
Recycling	a. 76.6% of net energy consumption respect to incineration [7] **+1** b. Avoid environmental costs of burning or landfilling [11] **+1** c. Requires 9 MJ/kg avoiding 80 MJ/kg for production of plastic bottles from virgin materials [12] **+1** d. Recycling is environmentally less desirable if there is the necessity of long range transportation [33] **0** e. Mechanical recycling is better than chemical recycling [33] **0** f. Environmentally preferable option [36] **+1** g. Environmental performance depends on plastic quality [36] **0**		Avoid environmental hazards [13] **+1**			Use of highly complicated waste stream without need of sorting [11] **+1**
Energy Recovery in Cement Mfg.	a. 60% of net energy consumption respect to incineration [7] **+1** b. Recovery eco-efficiency is comparable to other waste combustion technologies as incineration [32] **0**				a. Less amount of solid waste [36] **+1**	
Incineration	a) Worse cost and environmental performance than recovery in cement kiln [32] **-1**	a. Less favourable option [36] **-1**				
Incineration w/ Elec. Generation	a. Generation of 3 MJ/kg of electricity [12] **0** b. Worse cost and environmental performance than recovery in cement kiln [32] **-1**	a. Less favourable option [36] **-1**			a. Less amount of solid waste [36] **+1**	
Landfill	a. Worst eco-efficiency performance [32] **-1** b. Less favourable option [36] **-1**		a. Disposal has environmental consequences [14] **-1**	a. HCl emissions [19] **-1** b. PCDD emissions [19] **-1** c. Contamination of ashes with heavy metals [19] **-1**	a. Non degradable [19] **-1**	

7.9. Findings Table with Values for Used Tires for RQ2

7.9.1. Reuse

Resource consumption / conservation	a. Rethreading of tires avoid new tires production[13] **+1** b. Environmentally preferred solution with recycling [13] **+1** c. Worse environmental impact than other alternatives [28] **-1**
Global Warming	
CACs/Non hazardous air pollutant	
Metals & HAPs	
Eutrophication	
Operations Waste	
Economic Impacts	
Health and social impact	
Technical/market feasibility	

7.9.2. Recycling (use in asphalt road pavement)

Resource consumption / conservation	a. Additional grinding, mixing and heat lead to higher energy use [8] **-1** b. More asphalt is required relative to conventional asphalt [8] **-1** c. Environmentally preferred solution with re-use [13] **+1** d. Replacement for virgin rubber [13] **+1** e. Top 3 non renewable resources consumption performance [26] **+1** f. Top 3 water consumption performance [26] **+1**
Global Warming	a. Additional processing steps lead to increased GHG emissions [8,9] **-1,2**
CACs/Non hazardous air pollutant	a. Increase of NOx emissions [9] **-1** b. Increase of SOx emissions [9] **-1**
Metals & HAPs	a. Risk of heavy metal contamination of soil and groundwater [8] **-1**
Eutrophication	
Operations Waste	
Economic Impacts	a. High cost respect to other materials [8,25] **-1,2**
Health and social impact	a. Increase of chloride emissions in water [9] **-1**
Technical/market feasibility	a. Asphalt rubber pavement technologies require longer mixing periods and higher temperatures [8] **0** b. Barriers to use [25] **-1**

7.9.3. Recycling (use in artificial turf)

Resource consumption / conservation	a. Replacement for virgin rubber [13] **+1** b. Top 3 energy consumption performance [26] **+1**
Global Warming	a. Reduction of GHG emissions [9] **+1** b. Top 3 global warming performance [26] **+1**
CACs/Non hazardous air pollutant	a. Large reduction of VOCs [9] **+1** b. Top 3 acidifying gas emissions performance [26] **+1** c. Top 3 O3 performance [26] **+1**
Metals & HAPs	a. Greatest environmental emission reductions [9] **+1** b. PCDD emission reduction [9] **+1** c. Second largest heavy metal reduction benefits [9] **+1** d. Large reduction of ecotoxicity potential [9] **+1** e. Largest opportunities for reduction of O3 depletion potential [9] **+1**
Eutrophication	a. Eutrophication potential reduced [9] **+1** b. Top 3 eutrophication performance [26] **+1**
Operations Waste	a. Solid waste generation may increase [9] **-1**
Economic Impacts	a. High costs respect to other raw materials [25] **-1** b. Capital costs for equipment modification [25] **-1**
Health and social impact	a. Risks posed by exposure to rubber were within acceptable limits [9] **0** b. Continuing concerns about exposure of athletes to infectious diseases from bacteria that are harboured in artificial turf [9] **-1** c. Reduction of chloride emissions (large reduction in human cancer potential) [9] **+1** d. Reduction in human health impact and photochemical smog formation potential due to NOx and SO2 emissions reduction [9] **+1**
Technical/market feasibility	a. Limited potential for large scale utilisation due to the saturated market for artificial turf [9] **-1** b. Requires processing [25] **+1**

7.9.4. Recycling (others)

Resource consumption / conservation	a. Replacement for virgin rubber [13] **+1** b. Top 3 energy consumption performance [26] **+1**
Global Warming	a. Reduction of GHG emissions [9] **+1** b. Top 3 global warming performance [26] **+1**
CACs/Non hazardous air pollutant	a. Large reduction of VOCs [9] **+1** b. Top 3 acidifying gas emissions performance [26] **+1** c. Top 3 O3 performance [26] **+1**
Metals & HAPs	a. Greatest environmental emission reductions [9] **+1** b. PCDD emission reduction [9] **+1** c. Second largest heavy metal reduction benefits [9] **+1** d. Large reduction of ecotoxicity potential [9] **+1** e. Largest opportunities for reduction of O3 depletion potential [9] **+1**
Eutrophication	a. Eutrophication potential reduced [9] **+1** b. Top 3 eutrophication performance [26] **+1**
Operations Waste	a. Solid waste generation may increase [9] **-1**
Economic Impacts	a. High costs respect to other raw materials [25] **-1** b. Capital costs for equipment modification [25] **-1**
Health and social impact	a. Risks posed by b. exposure to rubber were within acceptable c. limits [9] **0** d. Continuing concerns about exposure of athletes to infectious diseases from bacteria e. that are harboured in artificial turf [9] **-1** f. Reduction of chloride emissions (large reduction in human cancer potential) [9] **+1** g. Reduction in human health impact and photochemical smog formation potential due to NOx and SO2 emissions reduction [9] **+1**
Technical/market feasibility	a. Limited potential for large scale utilisation due to the saturated market for artificial turf [9] **-1** b. Requires processing [25] **+1**

7.9.5. Energy Recovery in Cement Mfg.

Resource consumption / conservation	a. The presence of iron in tires reduces the need to purchase iron [8,26] **+1,2** b. Gypsum formed during tire combustion reduces the need to purchase gypsum as raw material [8] **+1** c. Reduction in water consumption [9] **+1** d. Energy gains near offset the costs of depleted resources [13] **0** e. Extraction of energy in an environmentally sound way [25] **+1** f. Best environmental result [28] **+1** g. Generation of highest amount of heat energy [37] **0** h. Positive environmental impact [38] **+1**
Global Warming	a. Reduction in GHG emissions [9] **+1** b. Top 3 global warming performance [26] **+1**
CACs/Non hazardous air pollutant	a. Reduction of VOCs [9] **+1** b. Minimized air pollution [9,25] **+1,2** c. Air pollution generated [19] **-1** d. Top 3 acidifying gas emissions performance [26] **+1** e. Highest amount of direct air emissions [37] **-1**
Metals & HAPs	a. No substantial increase in organic emissions [8] **0** b. Release of metal from cement produced in kilns accepting tires is likely to be minimal [8] **0** c. Reduction in air toxic emissions [9] **+1** d. Minimizes PCDD/PCDF [9,25] **+2,4** e. Largest heavy metal reduction benefits [9] **+1**
Eutrophication	a. Top 3 eutrophication performance [26] **+1**
Operations Waste	a. No residues, ashes included in the clinker [8,9,25] **+1,4** b. Indirect solid waste associated with upstream processes [9] **-1** c. Steel slug, zinc oxide and gypsum sold to other industries [25] **+1**
Economic Impacts	a. A plant using whole tires may be able to charge a tipping fee or, at least, to receive tires without cost [8] **+1** b. Large capital investment and operating expenses [8,25] **-1,2** c. Often no shredding needed [25,26] **0** d. Cheapest fuel except for local petcoke [25] **+1** e. Expense and downtime in environmental permitting process [25] **-1**
Health and social impact	a. Decrease in As emissions thereby reducing human carcinogenic potential [9] **+1** b. Reduction in lead as air emissions → reduction of human health non-cancer potential [9] **+1** c. Reduction in human health impact and photochemical smog formation potential due to NOx and SO2 emissions reduction [9] **+1** d. Relatively clean options [19] **+1**
Technical/market feasibility	a. Modification in the fuel feed system [8] **-1** b. Large market capacity [9] **+1** c. Competition with cheaper fossil fuels [25] **-1** d. Time required for permission [25] **-1** e. Handling equipment required [25] **-1**

7.9.6. Energy recovery in industrial boilers (e.g., paper/pulp)

Resource consumption / conservation	a. Energy gains near offset the costs of depleted resources [13] **0** b. Extraction of energy in an environmentally sound way [25] **+1**
Global Warming	
CACs/Non hazardous air pollutant	a. Reduction of NOx compared to burning coal [8,9] **+1,2** b. Reduction of SOx compared to burning coal [8,9] **+1,2** c. Increase of PM (likely to be enriched with Zn) compared to burning coal [8] **-1** d. Air pollution generated [19] **-1**
Metals & HAPs	a. Conflicting results about organic emissions [8] **0** b. Decrease of emissions of Cr, Cd and Pb [8] **+3** c. Increase of Zn emissions [8] **-1** d. Increase of chlorine emissions compared to burning coal [8] **-1** e. Significant increase of heavy metal emissions [9] **-1** f. Minimizes PCDD/PCDF [25] **+2**
Eutrophication	a. Eutrophication potential reduced [9] **+1**
Operations Waste	a. Increased concentration of Zn in ashes [8] **-1** b. Decreased concentration of Cd, Cr and Pb in ashes [8] **+3** c. Reduction of indirect solid waste associated with upstream processes [9] **+1**
Economic Impacts	a. The capital investment limited to the cost of TDF storage and metering equipment and the cost of environmental permit modifications [8] **+1** b. The cost of TDF relative to coal depends on the mill's current fuel purchase agreements, the cost of TDF and the location of the mill relative to TDF markets. [8] **0** c. Less capital investment than cement kiln [25] **+1** d. Often no shredding needed [25] **+1** e. High costs of wire-free tires [25] **-1** f. Low cost of alternate fuel [25] **+1**
Health and social impact	a. Increase in As emissions thereby increasing human carcinogenic potential [9] **-1** b. Increase of emissions of chloride and lead into the environment → increase of human health non-cancer potential [9] **-1** c. Reduction in human health impact and photochemical smog formation potential due to NOx and SO2 emissions reduction [9] **+1** d. Relatively clean options [19] **+1**
Technical/market feasibility	a. Competition with cheaper fossil fuels [25] **-1** b. Time required for permission [25] **-1** c. Handling equipment required [25] **-1**

7.9.7. Pyrolysis

Resource consumption / conservation	
Global Warming	
CACs/Non hazardous air pollutant	
Metals & HAPs	
Eutrophication	
Operations Waste	a. Production of steel, carbon black, oil and gas [19] **+1** b. Char needs to be upgraded [25] **0**
Economic Impacts	a. Capital and operating costs are a barrier [25] **-1** b. High costs for upgrading char by-products [25] **-1**
Health and social impact	
Technical/market feasibility	a. Variability of product quality and high capital costs are major constraints for the application of pyrolysis technology [19] **-1** b. Sustained commercial operation to be demonstrated [25] **0**

7.9.8. Incineration

Resource consumption / conservation	a. Neutral environmental impact [38] **0**
Global Warming	a. Reduction in GHG emissions [9] **+1**
CACs/Non hazardous air pollutant	
Metals & HAPs	a. Increase ecotoxicity due to an increase of chloride emissions in water [9] **-1**
Eutrophication	a. Eutrophication potential reduced [9] **+1**
Operations Waste	a. Reduction of solid waste production [9] **+1** b. Reduction of indirect solid waste associated with upstream processes [9] **+1**
Economic Impacts	
Health and social impact	a. Increase in chloride emissions in water → increase of human cancer potential [9] **-1** b. Increase of emissions of chloride and lead into the environment → increase of human health non-cancer potential [9] **-1**
Technical/market feasibility	

7.9.9. Incineration w/ Elec. Generation

Resource consumption / conservation	a. Energy gains near offset the costs of depleted resources [13] **0** b. Good environmental result [29] **+1**
Global Warming	
CACs/Non hazardous air pollutant	a. Air pollution generated [19] **-1**
Metals & HAPs	
Eutrophication	
Operations Waste	
Economic Impacts	a. Capital and operation costs [25] **-1**
Health and social impact	a. Relatively clean options [19] **+1**
Technical/market feasibility	

7.9.10. Landfill

Resource consumption / conservation	
Global Warming	
CACs/Non hazardous air pollutant	
Metals & HAPs	a. Release of PAHs, benzene and phenol [13] **-3**
Eutrophication	
Operations Waste	a. Intact for decades in landfills [19] **-1** b. Tendency to reach the top of landfills [25] **-1** c. Do not compact well (75% of whole tires is void) [25] **-1**
Economic Impacts	a. Whole tires landfilling avoids processing costs [25] **+1** b. Usually the cheapest alternative [25] **+1**
Health and social impact	a. Fire risk (decrease if tires are shredded) [19,25] **-1,2** b. Mosquitoes generation in whole tires [25] **-1**
Technical/market feasibility	

7.10. Findings Table with Values for Used Lubricating Oil for RQ2

7.10.1. Reuse

Resource Consumption / Conservation	a. Avoids imports of crude oil [13] **+1** b. 1,3 t of used oil vs. 10 t of crude oil to produce 1 t of high-grade base oil for the lubricant market, remaining fraction can be used for heating [13] **+1** c. Better results than energy recovery in cement kilns [29] **+1**
Global Warming	
CACs / Non-hazardous Air Pollutants	a. Avoid pollution of soil, groundwater and surface water [13] **+1**
Metals & HAPs	a. Better results than energy recovery in cement kilns [29] **+1**
Operations Waste	
Eutrophication potential	
Economic Impacts	
Health and social impact	a. Acidification indicators show better results than energy recovery in cement kilns [29] **+1** b. Nutrification indicators show better results than energy recovery in cement kilns [29] **+1**
Resource Consumption / Conservation	a. Avoids imports of crude oil [13] **+1** b. 1,3 t of used oil vs. 10 t of crude oil to produce 1 t of high-grade base oil for the lubricant market, remaining fraction can be used for heating [13] **+1** c. Better results than energy recovery in cement kilns [29] **+1**

7.10.2. Recycling: Acid clay extraction

Resource Consumption / Conservation	
Global Warming	a. Produces slightly lower GWP than that of solvent extraction process [10] **+1** b. Relatively high impact [10] **-1**
CACs / Non-hazardous Air Pollutants	
Metals & HAPs	a. Highest amount of acidification potential (SOx, NOx, HCl, HF and NH3) [10] **-1**
Operations Waste	
Eutrophication potential	
Economic Impacts	
Health and social impact	
Resource Consumption / Conservation	

7.10.3. Recycling: Solvent extraction

Resource Consumption / Conservation	
Global Warming	
CACs / Non-hazardous Air Pollutants	
Metals & HAPs	a. Lowest acidification potential (SOx, NOx, HCl, HF and NH3) [10] **-1** b. Releases less heavy metals than acid clay [10] **+1**
Operations Waste	
Eutrophication potential	a. Higher potential for eutrophication than acid clay [10] **-1**
Economic Impacts	
Health and social impact	
Resource Consumption / Conservation	

7.10.4. Energy Recovery in Cement Mfg.

Resource Consumption / Conservation	
Global Warming	a. Better results than regeneration/reuse [29] **+1**
CACs / Non-hazardous Air Pollutants	
Metals & HAPs	a. Generates considerably less acidification potential (SOx, NOx , HCl, HF and NH3) than those in boilers [10] **+1** b. Positive environmental performance with respect to heavy metal emissions [10] **+1** c. The direct burning in cement kiln and the burning in vaporizing burner are the most promising processes in terms of heavy metal emission [10] **+1**
Operations Waste	
Eutrophication potential	a. Higher than in the two recycling processes [10] **-1**
Economic Impacts	
Health and social impact	
Resource Consumption / Conservation	

7.10.5. Incineration

Resource Consumption / Conservation	
Global Warming	
CACs / Non-hazardous Air Pollutants	a. Health and environmental impact [13] **-1**
Metals & HAPs	a. Heavy metals released from vaporizing burner boiler are significantly lower with two orders of magnitude than those from small boilers and atomizing burner boilers [10] **+1** b. The direct burning in cement kiln and the burning in vaporizing burner are the most promising processes in terms of heavy metal emission [10] **+1**
Operations Waste	
Eutrophication potential	
Economic Impacts	
Health and social impact	
Resource Consumption / Conservation	

7.10.6. Energy recovery in industrial boilers

Resource Consumption / Conservation	
Global Warming	a. GWPs from these options dramatically higher than those from other options, and particularly when compared with combustion in cement kiln [10] **-1**
CACs / Non-hazardous Air Pollutants	
Metals & HAPs	
Operations Waste	
Eutrophication potential	
Economic Impacts	
Health and social impact	
Resource Consumption / Conservation	

7.10.7. Incineration w/ Elec. Generation

Resource Consumption / Conservation	
Global Warming	
CACs / Non-hazardous Air Pollutants	
Metals & HAPs	
Operations Waste	
Eutrophication potential	
Economic Impacts	
Health and social impact	
Resource Consumption / Conservation	

7.10.8. Landfill

Resource Consumption / Conservation	
Global Warming	
CACs / Non-hazardous Air Pollutants	a. Health and environmental impact [13] **-1**
Metals & HAPs	
Operations Waste	
Eutrophication potential	
Economic Impacts	
Health and social impact	
Resource Consumption / Conservation	

7.11. Findings Table with Values for Biomass for RQ2

Impact category	Anaerobic digestion	Recycling: fertilizers	Incineration w/Electricity generation	Pyrolysis	Gasification
Resource Consumption/ Conservation	a. Energy recovery 3,2 GJ/t [15] **+1** b. Nutrient recover [15] **+1**	a. Return of bio-waste to the ground as high quality fertilizers [13] **+1** b. Nutrient recover [15] **+1**	a. Energy recovery 2,7 GJ/t [15] **+1** b. Substitution of fossil fuels [15] **+1**	a. Energy recovery from incineration + energy in by-product char [15] **+1** b. Substitution of fossil fuels [15] **+1**	a. Energy recovery [15] **+1** b. Substitution of fossil fuels [15] **+1**
Global Warming	a. Methane emissions [15] **+1** b. CO2 neutral energy production in the form of electricity and heat [15] **+1**	a. 13-60% of carbon as CO2 [15] **+1**	a. 99% of carbon to air [15] **0**	a. 70-80% of carbon to air [15] **+1**	a. 98% of carbon to air [15] **0**
CACs / Non-hazardous Air Pollutants			a. NOx generation [15] **-1**	a. Less flue gas than incineration [15] **+1**	a. Less flue gas than incineration [15] **+1** b. NOx generation [15] **-1**
Metals & HAPs		a. Eliminate pathogens [15] **+1**		a. Retention of metals in the char [15] **+1** b. No PCDD/PCDF formation [15] **+2** c. HCl retained/distilled from the solid residue[15] **+1**	a. Retention of metals [15] **+1** b. Gas cleaning can remove pollutants [15] **0**
Operations Waste	a. 2-20% of residuals [15] **0** b. 30% fibres [15] **0** c. 23-65% fluids [15] **0**	a. 2-20% of residuals [15] **0** b. 13-23% compost **0**	a. 25% bottom ash (raw material for e.g., clinker/gravel material) [15] **+1** b. 3% metal [15] **0** c. 3% fly ash [15] **0**	a. 30-23% char [15] **0** b. 3% metal [15] **0** c. 2-3% flue gas residues [15] **0**	a. 15-25% vitrified bottom ash [15] **0** b. 3% metal [15] **9** c. 2% gas cleaning residues [15] **0**
Eutrophication potential					
Economic Impacts	a. Required waste source separation [15] **-1**	a. Cheap technology [15] **+1** b. Vector problem (proliferation of seagulls, rats and flies) [15] **-1** c. Skilled labour needed [15] **-1**	a. No need for sorting [15] **+1** b. Extensive investment [15] **-1** c. Extensive flue gas cleaning system [15] **-1**	a. Waste need to be shredded or sorted [15] **-1** b. Relative high-cost [15] **-1** c. Back-up supply of fuel is required during start-up [15] **-1**	a. Waste need to be shredded or sorted [15] **-1** b. Relative high-cost [15] **-1** c. Complicated gas clean-up for motor use [15] **-1**

7.12. Findings Table with Values for Hazardous Waste for RQ2

Impact category	Municipal solid waste incinerators	Cement kilns
Resource Consumption / Conservation		
Global Warming		
CACs / Non-hazardous Air Pollutants		
Metals & HAPs	a. Preferable respect to rotary kilns [39] **+1**	a. Controversial results when fuel has high metal content [39] **0** b. No convincing proof that cement kiln would not produce additional hazardous process emissions [39] **0**
Operations Waste		
Eutrophication potential		
Economic Impacts		
Health and social impact		

7.13. References used in Findings Tables for RQ1

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4	Sector report for the cement industry	UK Environment Agency
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6	Update on solid waste derived fuels for use in cement kilns - an international perspective	UK Environment Agency
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40	Dioxin/furan formation and release in the cement industry	W. van Loo
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57	Formation, release and control of dioxins in cement kilns	K.H. Karstensen
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About the Research

The Network for Business Sustainability commissioned this systematic review for the Cement Association of Canada. The research was subjected to a double-blind peer review by three experts from industry and academia.

The Network gratefully acknowledges the input of the following individuals for this report: Professor Doug Hooton (University of Toronto), Professor Heather MacLean (University of Toronto), Luc Robitaille (Holcim Canada) and John Cuddihy (Cement Association of Canada). Note: This report is authored exclusively by Vito Albino, Rosa Maria Dangelico, Angelo Natalicchio and Devrim Murat Yazan and the Network for Business Sustainability and does not necessarily reflect the views of the aforementioned individuals or their organizations.

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