The International Journal of Life Cycle Assessment
https://doi.org/10.1007/s11367-023-02159-9

LCA FOR MANUFACTURING AND NANOTECHNOLOGY

Analysing industrial symbiosis implementation in European cement industry: an applied life cycle assessment perspective

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Received: 5 July 2022 / Accepted: 12 March 2023
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Abstract

Purpose In the last 20 years, the implementation of industrial symbiosis (IS) has gained notoriety in the international context since it can create positive environmental, economic and social impacts. The literature suggests that the primary, extraction and conversion sectors are those with the highest potential for IS implementation. Among them, the cement industry has been recognized as an important sector due to its high potential to incorporate alternative resources in its production process. Nevertheless, this industrial sector is also characterised by its significant environmental impact; for this reason, it is necessary to evaluate the influence that circular business models, such as IS, can bring to this sector.

Method This study defined a set of scenarios for the implementation of IS in European industry based on literature review and expert consultation. A life cycle assessment–based analytical framework is developed to evaluate the impact of those measures in this sector. Lastly, a viability study dedicated to these scenarios was performed.

Results Results showed that IS implementation managed to produce a net positive impact, with a 6 to 12% GHG emission reduction being observed. Depending on the approach to biogenic carbon, industrial targets for 2030 can produce a reduction of either 80 kg or 39 kg of CO_2 per tonne of cement.

Conclusion IS implementation effectively reduces GHG emissions, albeit at a relatively smaller scale when compared with the overall emissions from cement manufacturing. The approach to biogenic carbon emissions poses a challenge, as the use (or omission) of these emissions affect the results substantially. Depending on the approach to biogenic carbon, 2030 objectives are either overachieved or underachieved.

Keywords Circular economy · Industrial symbiosis · Life cycle assessment · Cement

1 Introduction

Industrial symbiosis (IS) is a concept of industrial ecology introduced in the early 1970s (Short et al. 2014b), and it is also usually considered a circular economy business model (Albino and Fraccascia 2015; Baldassarre et al. 2019; Short et al. 2014a). Industrial symbiosis lies in a simple principle of sharing materials, resources and wastes between industrial players (Chertow 2007). One of the most accepted definitions of IS suggests that in a symbiotic relation instead of being thrown away or destroyed, surplus 'resources' generated by an industrial process are captured and redirected for use as a

Communicated by Yi Yang.

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'new' input into another process by other industries providing a mutual benefit or symbiosis (Lombardi and Laybourn 2012). Other authors suggest that this concept makes reference to an environmental metaphor, but in practical terms (Deutz and Lyons 2008; Gibbs 2008; Morales and Diemer 2019), both definitions refer to the same principle, to create an ecosystem represented by a group of industrial actors sharing waste, resources and utilities (Chertow 2000).

Over the years, the literature suggests that symbiotic initiatives are easily adapted to primary sectors (Vladimirova et al. 2018), since many of these sectors are highly dependent on the extraction of raw materials and involve the production of large amounts of surpluses in this process. These wastes can be valued as raw materials in other sectors. Among those sectors, the cement sector is considered to be one with a relevant potential since this industry can receive diverse surplus of other sectors, due to its capability to recover/introduce waste at various stages of its production process (Henriques et al. 2021; Quintana 2019). Nevertheless, this industrial sector is also characterised to involve significant environmental impacts (Cruz Juarez and Finnegan 2021), intensive consumption of raw materials and resources (Cantini et al. 2021). Cement production is an energy-intensive process that requires temperatures about 1450 °C in the kiln; for instance in 2010, the average thermal energy required to produce clinker was 3.7 kJ/ton. Each ton of cement requires up to 130 kg of fuel oil or equivalent and about 120 kWh of energy (Soyez and Graßl 2008) to be produced. The environmental impact of its production is also intensive with high emissions of greenhouse gases (GHGs). Currently, the amount of CO_2 emitted by the cement sector represents 5% of all anthropogenic emissions, where the EU is third with 5%. The overall production of 1 ton of cement usually emits between 0.5 and 1 ton of CO_2 (depending on the region) (NRMCA 2008; Andrew 2018).

In this sense, during the last years, stakeholders of this sector have gain awareness about the impact of this sector and had promoted several strategic perspectives to reduce the impacts. Among the most relevant initiatives, the 2050 Carbon Neutrality Roadmap promoted by the CEMBUREAU can be mentioned (CEMBUREAU 2013, 2020). This roadmap sets out the cement industry's ambition to reach net zero emissions along the cement and concrete value chain by 2050 (CEMBUREAU 2013, 2020). The roadmap looks at how CO_2 emissions can be reduced by acting at each stage of the value chain—clinker, cement, concrete, construction and (re)carbonation—to achieve zero net emissions by 2050. Another relevant initiative in this manner was promoted by in the European Green Deal (European Commission 2019), since it recognized that the circular economy goes hand in hand with carbon neutrality in the cement sector. Circularity is crucial to reduce emissions from clinker, which is the backbone of cement production. Currently, no recyclable waste is used to phase out fossil fuels from cement production. It will become even crucial tomorrow, as CO_2 captured during clinker manufacturing will be used in other industrial applications.

Besides the previously mentioned strategic perspectives, it is important to note that the academic community has developed many relevant studies in the last decade that aim to measure the environmental impacts of cement production. Most of these studies have been devoted to the environmental analysis of cement production in a specific country (García-Gusano et al. 2015; Ali et al. 2016; Moretti and Caro 2017) or to the improvement of processes and the definition of new cement production strategies (Valderrama et al. 2012; Feiz et al. 2015). Several studies have also been developed that relate industrial symbiosis implementation and life cycle assessment (Ismail 2020; Haq et al. 2021), and some of these have been applied to the cement sector (Hashimoto et al. 2010; Ammenberg et al. 2015). Please note that most of those studies focus on analysing environmental impacts in specific cases such as synergies (Liu et al. 2011), case studies (Daddi et al. 2017; Yu et al. 2015) or eco-industrial parks (Boix et al. 2017).

This work aims to quantify the impact of the IS implementation in the European cement industry. Our final goal is to assess the capacity if the measures proposed by the 2030 cement agenda are within the scope of the circular economy to achieve the proposed objectives. This paper pretends to advance the understanding of the contribution of industrial symbiosis implementation in the cement sector, by identifying the current practices and their environmental impact. The final contribution of this study is a compilation and characterisation of enabling best practices for IS in the cement sector and its environmental assessment. This information will contribute to the promotion of synergies in a more efficient manner. In order to achieve this objective, this study is based on various methods such as a literature review, the definition of industrial symbiosis potential scenarios and analysis-dedicated life cycle assessment. In this context, this paper was developed in order to answer the following research questions:

- *Which are the most widely implemented symbiosis scenarios in the European cement industry?*
- *What is the environmental impact associated to the industrial symbiosis potential scenarios in the European cement industry?*
- *Are the measures proposed at the European level capable to meeting the environmental objectives of the cement industry for 2030?*

This paper is structured as follows: Sect. 1, Introduction, discusses the scope of the article, contribution and motivations of the paper. Section 2 describes the research methodology adopted for this study. Section 3 introduces the life cycle assessment (LCA) performed in this article. Section 4 defines the scenarios for the validation. Sections 5 and 6 present the assessment of environmental impacts and the interpretation of the results. The conclusions are drawn in the last section (Sect. 7).

2 Research methodology

To achieve the objective of this paper, a research methodology was defined, based on a mixed approach (combining quantitative and qualitative methods). Figure 1 presents the research methodology developed in this research. In the next section, each of the methods is presented and described.

In the first stage of this research, the authors focus on the gathering information methods, which provide qualitative information. At this stage, we begin with a systematic literature review that enabled the identification of a set of case studies and knowledge. On the other hand, an expert consultation to a group of experts from the cement sector was developed, to provide technical information on the sectors, namely technologies or processes. These outputs enabled the definition of the most promising scenarios for the symbiosis. The second phase of the study was focused on methods that provide quantitative information, focused on a life cycle assessment to the four scenarios previously identified. The environmental impact for the scenarios supported the feasibility study that grant the analysis on the achievement of CEMBUREAU's 2030 objectives. Gathering information methods and analysis methods are comprehensively presented in the following sections.

2.1 Gathering information

2.1.1 Systematic literature review

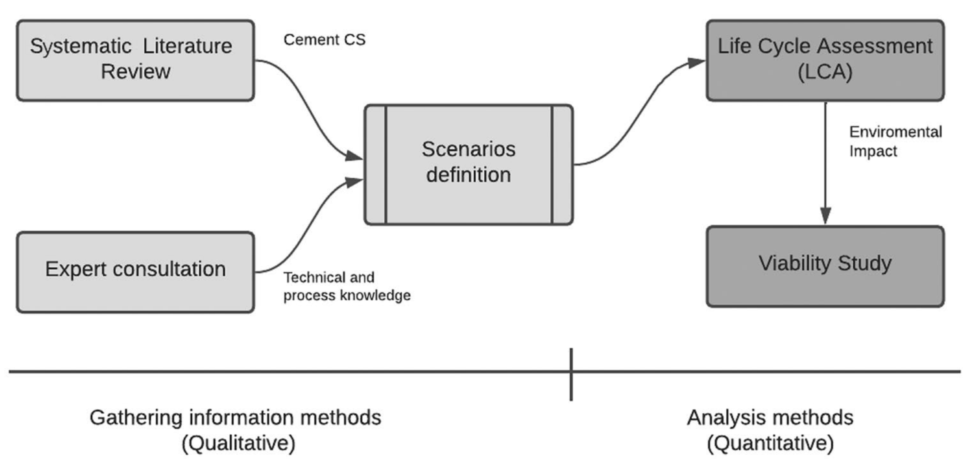
Our main information source for the characterisation of case studies was based on scientific peer-reviewed journal articles. The references were identified in the scientific databases Scopus and Google Scholar with the key words Industrial Symbiosis and Cement. Through the systematic literature review approach, it was possible to obtain an initial sample of 98 references. After discarding the non-relevant references through critical reading, a final sample of 45 articles was selected. From the analysis of the references, 15 implementation case studies (CSs) were finally identified. In addition, complementary research was developed through Internet searches for technical reports and technical documentation of European initiatives, such as European projects, sectoral clusters and IS networks.

2.1.2 Expert consultation

Parallel to the systematic review, experts were consulted to guarantee a correct representativeness of the industry. This expert consultation was carried out with the objective of deepening the valorisation scenarios identified through the literature review, namely in aspects such as quantities, technologies, processes and others. The experts consulted in this exercise were the following: process engineers of the two Portuguese cement producers in Portugal, specialist technicians, specialists in waste management, those responsible for associations/clusters of the cement and other relevant entities (6 experts in total). The main criteria for the selection of the experts were based on their experience and involvement in the production of cement.

The cement industry experts were consulted in dedicated discussion sessions which included visits to cement production units to gather knowledge directly from the factories. In these sessions, the following points were addressed: (i) promising scenarios for IS in the industry, (ii) the current state of the industry in those scenarios and (iii) specifics of the production process in factories. It is important to note that due to strict industrial confidentiality policies, the experts were not able to answer questionnaires regarding the manufacturing process. Specific data about the manufacturing process

Fig. 1 Research methodology



was sent (anonymized) by industrial experts to the authors via a neutral party.

According to the results of the expert's consultation, the experts considered that the 3 most promising scenarios are the use of alternative decarbonised raw materials, the use of alternative fuels and clinker substitution, in parallel to the focused on the use of alternative decarbonised raw materials. The greatest limitations to implement those scenarios are technical (adaptation of current technology/equipment and difficulties in pretreatment to guarantee the suitability of secondary and combustive raw materials are viable) and economic (the required investment to adaptation and additional cost operational).

3 Analysis method: LCA

LCA is a methodological framework to assess the potential environmental impacts of a system (product, processes, service, etc.) during its life cycle (Rebitzer et al. 2004). In this sense, this tool studies the environmental performance of products and services throughout its life cycle from raw material extraction to its end-of-life 'Cradle-to-Grave', or specific phases of a product life, for example from extraction to expedition 'Cradle-to-Gate'. The framework for life cycle assessment involves four main interconnected stages (ISO (International Organization for Standardization) 2004; Blengini 2006): goal and scope, inventory analysis, impact assessment and the interpretation. The first stage, goal and scope, describes the target of the assessment and establishes the context in which the analysis will be implemented and its limits are determined. The life cycle inventory (LCI) analysis identifies and quantifies the inputs and outputs within the system (energy and material consumption, emissions). The impact assessment calculates and quantifies the ecological and human health effects of the system inputs and outputs stipulated on the inventory analysis stage. Lastly, the interpretation stage gathers the results from previous stages, interprets them and delivers deductions that can provide the recipients with a LCA report. Here, this methodology is followed and implemented using the software SimaPro®.

3.1 Goals

This study aims to evaluate the environmental burden of a typical European cement plant and use it as a benchmark to assess the effectiveness of alternative scenarios associated to the implementation of IS practices contemplated by the sector. This project also assumes the secondary objective of assessing the potential of CEMBUREAU goals for 2030 (CEMBUREAU 2020), evaluating whether the proposed IS targets are sufficient to achieve its environmental aspirations. A customized model was developed instead of using readily available unit processes within LCA databases, a necessary approach to achieve the required level of detail to build, simulate and assess alternative scenarios; the following section describes the model context and setup procedure.

3.2 Scope

3.2.1 Analysis context: technical description of the product system manufacturing process

The first step in cement manufacturing is the production of clinker, which starts with the introduction of natural and secondary raw materials into the system. For external raw materials, transport is considered, whereas for the internal quarry, only the fuel used for the machinery is assumed (European Commission 2013). The raw materials enter a mill (denoted raw mill) and advance towards a preheater and precalciner system, before entering the rotary kiln. In this model, all main inputs and outputs related to the raw mill, preheater and precalciner are incorporated in the model through the electricity consumption and rotary kiln combustion processes. Once in the rotary kiln, the raw materials are heated up to 1450 °C to produce an artificial rock named clinker, the main constituent of cement. In the kiln, reactive materials go through numerous chemical reactions, noteworthily clinkering (1) and calcination (2) (European Commission 2013).

$$2CaO \cdot SiO_2 + CaO \rightarrow 3CaO \cdot SiO_2 \tag{1}$$

$$CaCO_3 \rightarrow CaO + CO_2 \tag{2}$$

The latter is responsible for the bulk CO_2 emissions of the whole cement plant, and therefore, a separate process was created in order to differentiate the CO_2 of the kiln combustion from calcination (European Commission 2013). Solid waste, sewage and heat waste formed during the entire clinker phase are considered in the model.

The total electricity consumption in this phase is condensed in the 'electricity' process, exception being pretreatment of alternative materials and fuels, whereas the consumption of electricity was disaggregated from the main process to reflect the effect of implementing alternative scenarios. Akin to electricity, water consumed through the clinker phase is contemplated in the water process.

Although incorporated in the clinker phase, the combustion within the rotary kiln is a process of high interest, as it is regarded as a main contributor for the cement environmental impact and a major target for improvement (CEMBUREAU 2013; European Commission 2013; ATIC - Associação Técnica da Indústria do Cimento 2021). An effort was made to disaggregate the process into the combustion of each individual fuel varieties (waste-based, biomass and fossil fuels), allowing for the recreation of various alternative scenarios. For each fuel, the transport is contemplated. Note that only CO_2 emissions (fossil and biogenic) were disaggregated per fuel type and the remaining pollutants are condensed in the primary process, being independent of the nature of the fuels used.

Cement phase is the final manufacturing stage, where cooled clinker reaches a cement mill, which mixes it with primary and secondary additives in predetermined ratios to create a specific blend of cement, which is then packed and dispatched (European Commission 2013). Both primary and secondary additives derive from external sources; as such, its transport is considered. The remaining inputs in the system are electricity consumption and a cement mill process which is solely used to account dust formation. Figures 2, 3 and 7 provide visualisations of the system and its boundaries.

3.2.2 Functional and declared units

The functional and declared units are parameters of reference to which the results of a LCA are attributed, and are applied to quantify the identified function(s) of the product (Blengini 2006), and these are differentiated depending whether the product system function is clearly identifiable or not. As cement is an intermediary product that can be used in multiple applications (mortar, concrete, among others), a 'declared unit' is utilised. In the end, all inputs and outputs within the model are correlated to this reference (Blengini 2006). Depending on the function(s) defined, unit and quantity are determined, which in the present case, the declared unit is 1 tonne of *ordinary Portland cement* (OPC), as it is representative of typical metrics used by the cement and construction sector to measure both consumption and production of cementitious products (Blengini 2006).

3.2.3 System boundaries and LCA stages

As this LCA study covers an intermediary product with an undefinable number of end-uses, the system boundaries shall not account the complete life cycle. Therefore, the following work is a *cradle-to-gate eco-profile*, covering all operations from the extraction, processing and transport of raw materials, until the product leaves the gates of the factory. The study coverage is equivalent to the product stage modules (modules A1 to A3). Figure 3 offers a view of the product system LCA stages considered in the assessment.

3.2.4 Selection of inventory data

Data related to the consumption of raw materials, kiln fuels and electric energy were obtained from consulting environmental declarations from two flagship cement-producing units from Portugal (CIMPOR (CIMPOR 2018) and SECIL (SECIL 2018)) and ecoinvent, whereas data regarding the average European rotary kiln emissions, waste and effluent formation were obtained from a LCA database (ecoinvent version 3) (ecoinvent 2020) and the Cement Sustainability Initiative (CSI) for CO_2 emissions (Climate Technology Center Network (CTCN) 2011; WBCSD Cement Sustainability Initiative (CSI) 2014). As for the production of electric energy, it was modelled based on the 2018 Portuguese electricity mix supplied by REN (a Portuguese energy sector company) using generic unit processes from ecoinvent (REN 2019; ecoinvent 2020). Information for the remaining processes (e.g. extraction of externally sourced raw materials, production of ancillary materials, transport to the factory gate, internal transport and others) was extracted from ecoinvent v3 (ecoinvent 2020). The objectives for the alternative scenarios were obtained from CEMBUREAU (a European

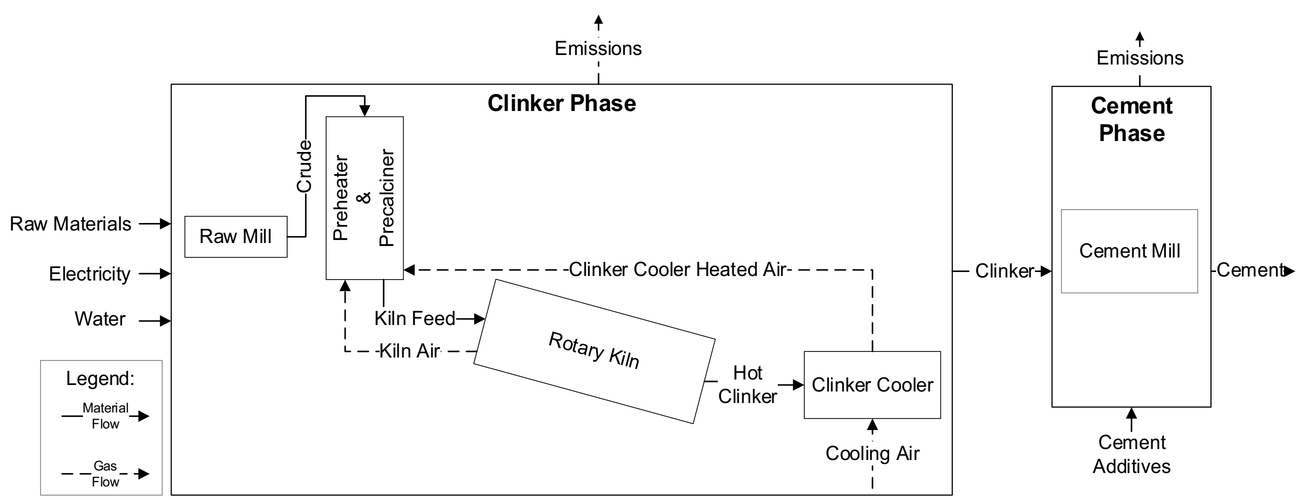


Fig. 2 Simplified diagram of a typical dry process cement production chain. Adapted from European Commission (2013)

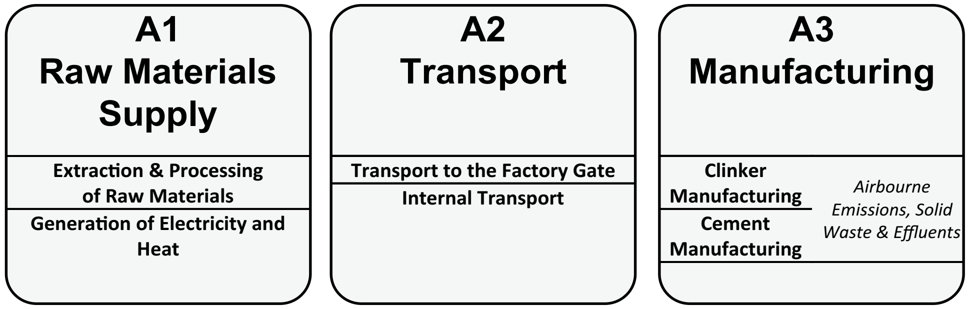


Fig. 3 Life cycle stages covered by the study

cement association) carbon neutrality roadmap (CEMBUREAU 2013, 2020).

Additionally, the best available techniques document from the European Commission (EC) (European Commission 2013), consultations from ATIC (a Portuguese technical association for the cement industry) (ATIC - Associação Técnica da Indústria do Cimento 2021) and inquiries to the industrial experts were used for the setup of customized unit processes and for validation of the model structure. Data quality varies depending on the source; some were collected directly from producers' industrial statistics (primary data), while others were obtained from published sources and generic databases (secondary data). Data quality assessment can be found in the supplementary material (Table 1).

3.2.5 Biogenic carbon inventory

Numerous academic publications tend to immediately consider the biogenic carbon neutrality assumption rather than applying a complete inventory as suggested by usual LCA guidelines (Wiloso et al. 2016). Reasoning being that the biogenic carbon released during combustion (or decomposition) was absorbed during biomass growth, therefore, no net increase in GHG should be reported (Wiloso et al. 2016).

The Intergovernmental Panel on Climate Change (IPCC) and the United Nations Framework Convention on Climate Change (UNFCCC) adopts a 'carbon stock' approach rather than 'input–output flow' to biogenic carbon (Wiloso et al. 2016). An interpretation of the aforementioned approach is that if biomass from a forest is cleared and, in a later stage, combusted as a source of energy, carbon could be considered as land use; as such, emissions from combustion should be considered zero to avoid double counting (Wiloso et al. 2016). Such argument is regularly used to justify the biogenic carbon neutrality; however, authors such as Haberl et al. (2012) consider this approach to be a misapplication of the original guidelines, as a complete inventory guarantees an accurate depiction of overall carbon balances.

Wiloso et al. (2016) studied the effect of biogenic carbon inventory and found that the neutrality assumption might introduce a bias towards the 'real' value obtained from a complete inventory, making the overall GHG emissions erroneously valued in cases such as studies with incomplete boundaries. Since the life cycle boundaries for intermediary cementitious products are limited to 'cradle-to-gate' and encompass the use of biomass as a primary source of energy, this study could be particularly susceptible (Wiloso et al. 2016). In response to this susceptibility, the study will compare results using a 'complete inventory' with the 'biogenic carbon neutrality' approach to assess the magnitude of this effect and further discuss the procedures suggested by EN 15804: A2 compared with other methods.

3.3 Life cycle impact analysis: indicators for analysis of environmental impacts

The selection of a life cycle impact analysis (LCIA) method to assess the impact provides a crucial step in establishing a suitable impact assessment and allowing accurate comparisons with similar products. The selected method is the 'EN 15804 + A2', available in the software SimaPro® 9.2, based on 'Environmental Footprint' (EF) 3.0 (European Commission 2021) method but adapted for EN 15804 (2019 A2 amendment) standard that covers Environmental Product Declarations (EPDs) for construction products. Compared to previous editions, the A2 revision brings a novel approach to carbon accounting and revamps the handling of biogenic carbon emissions and storage, by changing the set of characterisation factors from the CML methodology to EF 3.0. In essence, the climate change impact category is now divided into four separate subcategories: total, fossil, biogenic and land use and land use changes (LULUCs), rather than reporting as a single category encapsulating all carbon emissions regardless of its nature. The novel subcategory 'Climate Change – Biogenic' then tracks and quantifies the uptake and release of biogenic carbon allowing for a better understanding of these emissions (Technical Committee CEN/TC 350 2013).

Elected due its specificality towards the construction sector, this LCIA method is aligned with EF methodology apart from the approach to biogenic carbon, as the standard assumes that biogenic carbon produces the same effect on climate change as fossil carbon (non-neutral), but it can be neutralized by its removal from the atmosphere again (Technical Committee CEN/TC 350 2013). While the LCIA does cover all core impact categories from EN 15804 + A2, this study is focused on the category 'Climate Change' that is the effect from GHG emission on the climate change and global warming, as it is considered the major environmental concern of the European cement sector (CEMBUREAU 2020; ATIC - Associação Técnica da Indústria do Cimento 2021). Table 1 lists the selected impact categories, and a full list for all EN 15804: A2 core impact categories is available in the supplementary material (Table 2).

4 Definition of scenarios

In the next section, the results of the literature review process are presented. Based on the results, the promising scenarios for industrial symbiosis in the cement sector are defined. The development of IS scenarios was based on input received upon expert consultation, who revealed the existence of the numerous carbon neutrality roadmaps and industrial objectives set for the European cement sector, such as the 2050 Carbon Neutrality Roadmap developed by CEMBUREAU (a European cement association).

This specific roadmap itself establishes quantifiable objectives for achieving its environmental goals (e.g. 60% calorific substitution with alternative fuels); as such, these can easily be adopted to serve as a basis to establish the IS scenarios used for the analytical study. Moreover, the input from experts was revealed to be critical in choosing the most relevant measures that are advocated by the aforementioned roadmaps, guiding the authors to establish IS scenarios which are simultaneously based on real-world proposals by the industrial sector while also being academically pertinent.

4.1 Industrial symbiosis in the cement sector: case studies

The case studies are associated to diverse economic sectors and countries, where the common factor between them is the symbiotic exchanges with the cement sector. In addition, it was also possible to identify other important aspects such as geographical distribution, economic sectors and the measures implemented. Table 2 shows the final sample of case studies.

4.2 Descriptive results of case studies

Regarding the scientific publications, in the last 8 years, there has been an increase in the number of publications concerning the cement involvement in the symbiotic initiatives in peer-reviewed journals. Figure 4 represents (a) geographical distribution, (b) the number of published papers per year and (c) journals.

In terms of publication typology, our main information source for the characterisation of the case was based on scientific peer-reviewed journal articles. Furthermore, other publications such as the technical reports, conference papers and technical documentation were also considered.

In the sample, most of the studies were published in journals with topics related to cleaner production, and it represents more than a third of the total publications. The rest of the publications are in different journals with diverse topics such as energy, environmental policies and green technology. Furthermore, 17% of the total publications are conference papers, proceedings, book chapters and reviews, among others. In terms of geographical distribution, it is important to note that all the cases are framed within the European scope due to the similarity of cement production processes in this region.

4.3 Cross-sectorial synergies in the cement sector

The stream exchanges that can take place within the scope of IS are commonly known as synergies. These synergies are classified into two main groups: (1) direct synergies, corresponding to cases where the stream is directly used, or with light technology (e.g. crusher, packaging, transport, storage, collection/distribution), as a substitute from a raw one (Stéphane et al. 2019), and (2) indirect synergies, if the stream requires a modification or a treatment (e.g. extraction, filtration, separation, purification, cleaning or transformation) that can be done by either an involved stakeholder or a third party (Stéphane et al. 2019). It is important to note that the synergies considered for the purpose of this study were, in perspective, only involving cross-sector synergies with the

Table 1 Selected impact categories for LCIA (adapted from Technical Committee CEN/TC 350 (2013))

Impact category	Indicator	Unit
Climate change-total	Global warming potential total (GWP-total)	kg CO_2 eq
Climate change-fossil	Global warming potential fossil fuels (GWP-fossil)	kg CO_2 eq
Climate change-biogenic	Global warming potential biogenic (GWP-biogenic)	kg CO_2 eq
Climate change-land use and land use change	Global warming potential land use and land use change (GWP-luluc)	kg CO_2 eq

Table 2 Characterisation of case studies

Case	Denomination case	Location	No. of synergies	Year	Source
CS1	Austrian cement industry	Austria	2	2017	(Gesch 2015)
CS2	Lafarge Holcim Austria	Austria	1	2017	(Lafarge Holcim Austria 2015)
CS3	Styria	Austria	8	2013	(Zhang et al. 2013)
CS4	The Kalundborg industrial cluster	Denmark	1	2009	(Adamides and Mouzakitis 2009; Jacobsen 2006)
CS5	Aalborg	Denmark	9	2015	(Aalborg Portland 2015)
CS6	Dunkirk	France	1	2019	(Morales and Diemer 2019)
CS7	Cluster West	Germany	1	2013	(Ammenberg et al. 2015)
CS8	Taranto	Italy	2	2014	(Notarnicola et al. 2016)
CS9	IJmuiden	Netherlands	2	2015	(Deshpande 2015)
CS10	The Rotterdam Harbour and Industry Complex	Netherlands	2	2007	(Baas and Boons 2007; Martin and Harris 2018)
CS11	Geocycle Poland	Poland	1	2017	(Geocycle 2018)
CS12	Lisbon metropolitan area	Portugal	1	2014	(Patrício et al. 2015)
CS13	Spanish cement industry	Spain	4	2015	(Institut Cerdà 2017)
CS14	The Forth Valley Area Case (Dunbar)	UK	3	2004	(Harris 2004)
CS15	O.C.O Technology	UK	3	2005	(O.C.O Technology 2010)

cement sector as a receptor, and the potential of the cement sector being a waste donor was not considered. Among the cross-sector synergies within the CS, the two most important sender sectors are energy and steel, being represented by 20% and 19%, respectively. Other sectors with an important representation were the pulp and paper industry (12%), mineral extraction (6%) and chemicals (6%). The management, transportation and light technology of wastes like management and municipal waste sectors involve 16%. The sample also has a group of diverse sectors with slight representation that have been grouped into the category 'others', and these sectors correspond mainly to automobile shredder activities, construction and petrochemical. Figure 5 shows (a) the distribution of cross-sector synergies and (b) the distribution of synergy typologies for the final sample.

Additionally, in all cases, the synergies occur from an external perspective, that is, external synergies, where the materials to be valued can be sent to a cement plant. In most cases, few synergies per case were identified, usually 1–4 synergies.

4.4 Content results of case studies

The cement industry is one of the major recipients of waste in the European Union. According to CEMBUREAU, about 5% of the raw materials used in the production of clinker in the EU consisted of recycled material, and 46% of the fuel mix across Europe is alternative fuels (CEMBUREAU 2013, 2020). The preliminary results of the literature review and cases suggest that within the scope of industrial symbiosis, there are two categories of substitution flow for the implementation of synergies: energy and raw materials. Figure 6 shows the areas and categorization of the various IS measures implemented in the cement sector.

It is important to highlight two aspects: (i) industrial symbiosis also includes the share of facilities, infrastructure and services, but for the purposes of this study, those approaches were not targeted, and (ii) there are other recovery methods in the cement sector, but for the purposes of this study, it only considered those that have been developing

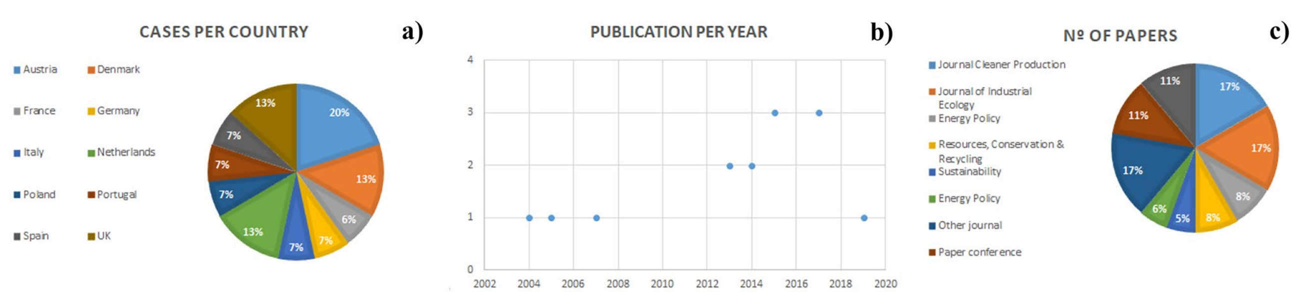


Fig. 4 **a** Geographical distribution, **b** the number of published papers per year and **c** journals

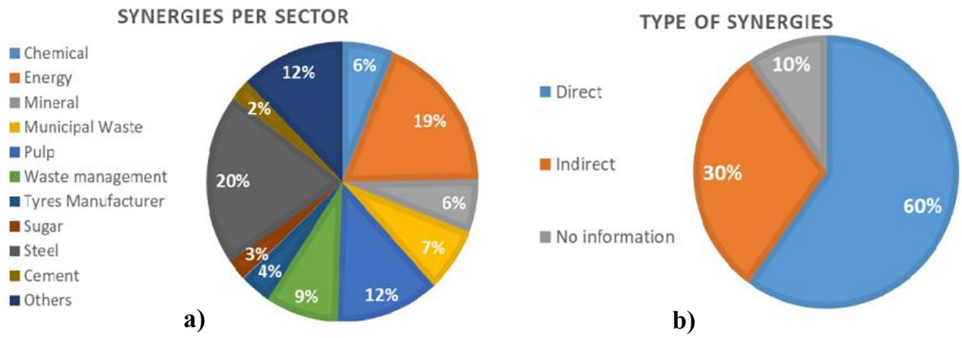


Fig. 5 **a** The distribution of cross-sector synergies and **b** the distribution of synergy typologies for the final sample

IS initiatives. For the purposes of the next chapter, we have defined 4 final scenarios for environmental assessment: (i) alternative decarbonised raw materials, (ii) alternative fuels (including biomass), (iii) clinker substitution and (iv) 2030 IS measures.

5 Assessing environmental impacts for the European cement industry

To evaluate the environmental impact incurring from cement manufacturing, a life cycle assessment methodology was implemented. The framework applied during the following section is founded on the goals and scope established on Sect. 3, starting with the setup of the inventory. The ensuing section will handle the impact assessment results and its interpretation.

5.1 Assumptions

Important assumptions and compromises were made in order to simplify the model while maintaining accurate and representative results. Assumptions were based on knowledge collected from literature and input from experts within the Portuguese cement industry.

- *All clinker is consumed to produce cement: Despite clinker being sold as a product as well, for simplification proposes, it is assumed that all clinker is used in cement manufacture.*
- *There is no internal valorisation of waste: Cement industry produces negligible amounts of waste compared to its useful output; it is assumed that waste is formed but is not recycled internally.*
- *Secondary materials and alternative fuels do not have an associated environmental burden: Processing of waste is assigned to the system that generates it, until the end-of-waste state is reached—'Polluter Pays Principle'. All secondary materials and alternative fuels are considered external waste that is valorised within the cement factory, and no environmental impact is attributed besides of the transport to its gate* (Technical Committee CEN/TC 350 2013).
- *All secondary raw materials are decarbonised: The secondary materials that enter in the clinker phase do not contribute to the calcination reaction and its associated emissions.*

5.2 LCI analysis

5.2.1 Geographical and temporal coverage

As this study is intended to quantify the environmental impact of a typical European cement plant, the selected region of interest is Europe. However, as the study is intended to provide a detailed analysis, part of the detailed data was obtained from the Portuguese cement sector (CIMPOR 2018; SECIL 2018; ATIC - Associação Técnica da Indústria do Cimento 2021), and the model is biased towards a Portuguese reality. The Portuguese-specific data was mainly used to fill gaps and provide the correct level of detail to model the alternative scenarios (e.g. the rotary kiln fuel mix, electricity consumption division between clinker and cement phase, the raw materials mix or the type of secondary raw materials used). Being a member of CEMBUREAU, the Portuguese cement industry is compliant with the

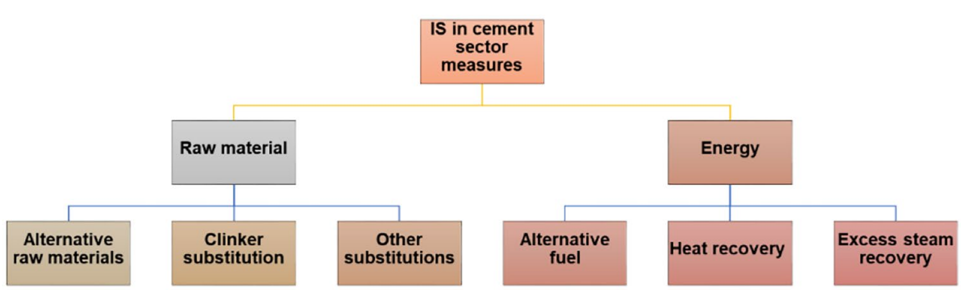


Fig. 6 Industrial symbiosis implementation synergy categories

European reality (ATIC - Associação Técnica da Indústria do Cimento 2019). The yearly range of the gathered data varies from 2006 to 2019, with its majority concerning the late 2010s, and as such, the temporal coverage for the model is the 2010 decade (CIMPOR 2018; SECIL 2018; European Commission 2013; CEMBUREAU 2020; ecoinvent 2020).

5.2.2 Flows associated with module A1: extraction and processing of raw materials

Cement is a resource-intensive process that consumes high volumes of raw materials. Table 3 depicts the typical average material and water consumption in a European cement plant. Data from Portuguese cement producers reveals that its use of secondary raw materials is still residual, with around 50 kg being consumed per tonne of clinker (CIMPOR 2018; SECIL 2018; ATIC - Associação Técnica da Indústria do Cimento 2021). Sources from the same industry refer to this poor replacement rate to be related with the difficulties in pretreatment and a very strict selection of materials that do not damage the equipment or affect the product quality. The consumption of clinker per tonne of cement was assumed to be 770 kg in accordance with CEMBUREAU latest information regarding clinker integration from 2017 (CEMBUREAU 2020). The use of clinker substitutes (fly ash) was described to be around 6 kg per tonne of cement (CIMPOR 2018; SECIL 2018).

5.2.3 Flows associated with module A1: generation of electric energy

Electricity is mainly consumed in mills and exhaust fans, accounting together with more than 80% of the total electricity use, a typical demand varying between 90 and 150 kWh per tonne of cement (European Commission 2013). For the inventory, data was mainly based on SECIL-OUTÃO, due to the fact that its environmental declaration distinguishes electricity consumption between the clinker phase and the cement phase (SECIL 2018). It is assumed that the processes in the clinker phase consume around 47.5% of the electricity demand, whereas the cement phase (and other activities within the plant) consumes 52.5%, 57 kWh/tonne cement and 63 kWh/tonne cement, respectively, as seen in Table 4 (SECIL 2018). The chosen electricity mix was Portugal 2018, which can have a mild impact on results due to the high incidence of renewable energy sources in the country (REN 2019). According to an environmental report regarding co-processing in Portugal promoted by AVE (an environmental management entity for co-processing in the Portuguese cement industry), the energy used for preprocessing of secondary raw materials and fuels was assumed to be 20 kWh per tonne of processed material (around 3 kWh/tonne cement) being included in the consumption of each phase (3drivers - Engenharia Inovação e Ambiente; AVE - Gestão Ambiental e Valorização Energética SA 2018). The total electricity consumption is around 120 kWh per tonne of cement (SECIL 2018).

5.2.4 Flows associated with module A2: transport to the factory gate

Table 5 lists the transport of the main materials/fuels used for the inventory. However, to approach the transport of goods, the concept of tonne-kilometre (tkm) should be introduced, a measure of freight transport which represents the transport of 1 tonne of materials using a specific transportation method (e.g.

Table 3 Material and water consumption for the manufacture of cement

	Example of waste	Quantity
Consumption of primary materials		
Materials		
Limestone + marl		1.26 t/t clinker (CIMPOR 2018; SECIL 2018; ecoinvent 2020)
Clay		304.6 kg/t clinker (ecoinvent 2020)
Sand		9.4 kg/t clinker (ecoinvent 2020)
Clinker consumed		770 kg/t cement (CEMBUREAU 2020)
Gypsum		60.5 kg/t cement (CIMPOR 2018; SECIL 2018; ecoinvent 2020)
Filer (rich limestone)		163.5 kg/t cement (CIMPOR 2018; SECIL 2018; ecoinvent 2020)
Water		1.62 m^3/kg clinker (ecoinvent 2020)
Consumption of secondary materials		
Materials substituted		
Silicon (Si)	Spend foundry sand; silica fume	19 kg/t clinker (CIMPOR 2018; SECIL 2018)
Calcium (Ca)	Industrial lime; carbide sludge	16 kg/t clinker (CIMPOR 2018; SECIL 2018)
Iron (Fe)	Pyrite cinder; iron slag	9 kg/t clinker (CIMPOR 2018; SECIL 2018)
Alumina (A_2O_3)	Industrial sludge	6 kg/t clinker (CIMPOR 2018; SECIL 2018)
Clinker	Fly ash	6 kg/t cement (CIMPOR 2018; SECIL 2018)

Table 4 Electricity consumption in kWh, per tonne of final product (cement), for different production phases

Production phase	Electricity consumption (kWh/tonne cement)
Clinker phase	*57* (69.4 kWh/tonne clinker) (SECIL 2018)
Clinker production (main processes)	54.1 (SECIL 2018)
Fuel pretreatment	2.1 (SECIL 2018, 3drivers - Engenharia Inovação e Ambiente; AVE - Gestão Ambiental e Valorização Energética SA 2018)
Secondary raw material pretreatment	0.8 (SECIL 2018, 3drivers - Engenharia Inovação e Ambiente; AVE - Gestão Ambiental e Valorização Energética SA 2018)
Cement phase (+ other activities)	*63* (SECIL 2018)
Cement production (main processes)	55.9 (SECIL 2018)
Secondary cement additive pretreatment	0.1 (SECIL 2018, 3drivers - Engenharia Inovação e Ambiente; AVE - Gestão Ambiental e Valorização Energética SA 2018)
Other activities (details non-disclosed)	7 (SECIL 2018)
Total	*120* (SECIL 2018)

water, road, rail) over a distance of 1 km. The report regarding co-processing in Portugal promoted by AVE refers to an average transportation of 200 km by road transport of alternative raw materials. For alternative fuels, 51% of fuels came from overseas (with an average distance of 6000 km) and 49% by road with a distance of 200 km (3drivers - Engenharia Inovação e Ambiente; AVE - Gestão Ambiental e Valorização Energética SA 2018). For conventional raw materials and fuels, transportation data was obtained from ecoinvent v3 (ecoinvent 2020).

5.2.5 Flows associated with module A3: manufacture: rotary kiln, waste and effluents

The energy demand is determined by the thermal input necessary for the clinker burning reactions and raw material preheating. The type of process, kiln, size and blends of cement being produced influence the energy demand (European Commission 2013). A typical dry process plant with a multistage cyclone preheater, precalciner and a dry rotary kiln can consume between 3 and 4 GJ per tonne of clinker (European Commission 2013). Based on information supplied by ATIC, the European Commission and ecoinvent, an average thermal energy consumption of 3.5 GJ per tonne of clinker was established, on the assumption that the system is based on a dry process with preheaters and precalciner (European Commission 2013; ecoinvent 2020; ATIC - Associação Técnica da Indústria do Cimento 2021).

A variety of fuels can be used to fulfil the thermal energy demand; conventional fuels are fossil based which include coal, petcoke, fuel oil and natural gas. The type of fossil fuel

Table 5 Freight transport of materials and fuels

Material or fuel	Consumption (kg/t clinker)	Average distance (km)	Freight transport (tkm)	Transport method
Sand	9.42	47	0.4	Multiple (ecoinvent 2020)
Clay	305	19	5.8	Road (ecoinvent 2020)
Secondary raw materials	50	200	10	Road (3drivers - Engenharia Inovação e Ambiente and AVE - Gestão Ambiental e Valorização Energética SA 2018)
Cement additives	224 kg/t cement	200	44.8	Road (ecoinvent 2020)
Cement alt. additives	6 kg/t cement	200	1.2	Road (3drivers - Engenharia Inovação e Ambiente and AVE - Gestão Ambiental e Valorização Energética SA 2018)
Petcoke	73	537	39.2	Multiple (ecoinvent 2020)
Fuel oil	0.32	1344	0.4	Multiple (ecoinvent 2020)
Alternative fuels	35.7	200	3.5	49% road (3drivers - Engenharia Inovação e Ambiente and AVE - Gestão Ambiental e Valorização Energética SA 2018)
		6000	109	51% sea (3drivers - Engenharia Inovação e Ambiente and AVE - Gestão Ambiental e Valorização Energética SA 2018)
Biomass	27.5	200	2.7	49% road (3drivers - Engenharia Inovação e Ambiente and AVE - Gestão Ambiental e Valorização Energética SA 2018)
		6000	84.15	51% sea (3drivers - Engenharia Inovação e Ambiente and AVE - Gestão Ambiental e Valorização Energética SA 2018)

used depends on the availability, logistics, transport, price and type of cement being produced, with petcoke and coal being the most common (European Commission 2013). Waste is widely used as an alternative fuel, with its consumption expanding continuously within the European cement industry (European Commission 2013; CEMBUREAU 2020). However, it should be noted that, unlike conventional fuels which have a relatively stable and predictable calorific value, waste can vary widely, affecting the quality of the process and the fuel input requirements (European Commission 2013).

Alternative fuels and biomass consumption should not be compared with conventional fuels, as the heat of combustion tends to be less stable than its fossil counterpart, and the presence of moisture affects its performance as well. The rate of substitution must be measured on calorific value instead of units of mass. More information regarding alternative fuels is available in the supplementary material (Table 3). Table 6 depicts the fuel consumption per ton of clinker and its emission factor. Note that the fuel consumption ratios were adopted from the Portuguese cement industry (CIMPOR 2018; SECIL 2018; ATIC - Associação Técnica da Indústria do Cimento 2021), the heating values from ecoinvent v3 (ecoinvent 2020) and the CO_2 emission factors from the CSI CO_2 protocol (Climate Technology Center Network (CTCN) 2011).

The main source of airborne emissions is the kiln, mainly from the physicochemical reactions of the raw materials and fuel combustion. The main fractions of the kiln emissions to the air are CO_2 from the calcination reaction and fuel combustion, nitrogen from the combustion, water steam and excess oxygen (European Commission 2013). The kiln emissions vary according to diverse factors such as the type of raw materials used, fuel mixture or even the national environmental policies. Concerning residue formation, an assumption was made that no internal valorisation was performed; therefore, all residue formed leaves the system borders for treatment. Table 7 lists the typical direct emissions (airborne, solid and effluents) from European cement units, and the selected values used in the inventory.

Note that these values are yearly averages based on different measures using various techniques. The CO_2 emissions originated from calcination were obtained from CSI CO_2 protocol (Climate Technology Center Network (CTCN) 2011) which determines the amount to be 525 kg of CO_2 per tonne of clinker produced. Since it is assumed that secondary raw materials are decarbonised, the calcination emissions must be associated with the natural raw material input, not the clinker output. In the LCI model, 525 kg of CO_2 is generated per 1.57 tonnes of natural raw materials that enter the rotary kiln (the amount required to produce 1 tonne of clinker).

As for the remaining airborne pollutants, values were adapted from the unit process 'heat production, at coal coke industrial furnace 1-10 MW RoW' (Rest of the World) from ecoinvent (ecoinvent 2020). Information regarding waste and effluents was obtained from the unit process 'clinker production Europe without Switzerland' (ecoinvent 2020).

5.2.6 Inventory flow chart

Figure 7 depicts the flow charts for the author's model as described in Sect. 3.2.3. Detailed diagrams illustrating the model are available in the supplementary material (Figs. 1, 2 and 3).

6 Interpretation of LCA results

The following chapter aims to interpret the critically analysed results from the LCA model and subsequently evaluate whether CEMBUREAU goals are achievable.

Table 6 Fuel consumption (by weight and energy) and its emission factor

Types of fuels	Specific fuel consumption (kg/t clinker)	Energy consumed (MJ/t clinker)	Emission factor (kg CO_2/GJ)	Total kiln energy (fuel mix) (%)
Petcoke	73 (CIMPOR 2018; SECIL 2018)	2088 (ecoinvent 2020)	92.8 (Climate Technology Center Network (CTCN) 2011)	60 (CIMPOR 2018; SECIL 2018)
Fuel oil	0.32 (CIMPOR 2018; SECIL 2018)	12 (ecoinvent 2020)	77.4 (Climate Technology Center Network (CTCN) 2011)	
Alt. fuels	35.7 (CIMPOR 2018; SECIL 2018)	875 (ecoinvent 2020)	82 (4.4 Biogenic) (Climate Technology Center Network (CTCN) 2011)	25 (CIMPOR 2018; SECIL 2018)
Biomass	27.5 (CIMPOR 2018; SECIL 2018)	525 (ecoinvent 2020)	110 Biogenic (Climate Technology Center Network (CTCN) 2011)	15 (CIMPOR 2018; SECIL 2018)
Diesel	0.4 (CIMPOR 2018; SECIL 2018)	20.1 (ecoinvent 2020)	74.1 (Climate Technology Center Network (CTCN) 2011)	NA

Table 7 Typical direct emissions for European cement kilns, and values selected for the inventory

	Typical emissions (kg/t clinker)	Reported emissions	
		kg/t clinker	kg/t cement
Pollutant			
Carbon dioxide (CO_2), fossil, combustion	255–379*	263	202
CO_2, biogenic, combustion	51–77*	62	47
CO_2, calcination reaction	525	525	404
CO_2, total	844–1000	850	653
Carbon monoxide (CO)	0.46 to 4.6	0.438	0.337
Nitrogen oxides (NO_x)	0.33–4.67	0.875	0.674
Sulphur dioxide (SO_2)	≤ 11.12	2.19	1.68
Total organic carbon (TOC)	0.0023–0.138	0.070	0.054
Hydrogen fluoride (HF) (g/t)	0.021–2.3	1.16	0.894
Hydrochloric acid (HCl) (g/t)	0.046–46	23	17.7
Polychlorinated dibenzo(p) dioxin and furan (PCDD/F) (ng/t)	0.0276–627	87.5	67.39
Particulates (pg/t)	0.62–522	0.25	0.20
Heat waste (MJ)	150	150	116
Waste & effluent formation			
Wastewater (m^3)	NA	1.66	1.28
Inert waste for final disposal (g)	NA	80	62
Solid waste (g)	NA	45	35
Source	(Climate Technology Center Network (CTCN) 2011; ecoinvent 2020)	(Climate Technology Center Network (CTCN) 2011; ecoinvent 2020)	(Climate Technology Center Network (CTCN) 2011; ecoinvent 2020)

*Obtained using the overall typical total CO_2 emissions from the literature; disaggregation was applied using the emission factors in Table 6, a typical European fuel mix reported by CEMBUREAU for the year 2017 (54% fossil, 30% alternative and 16% biomass (thermal output percentage)) (CEMBUREAU 2020)

6.1 Characterisation

Table 8 provides the characterisation results for the impact category climate change distributed between each life cycle stages. It is evident that module A3 (manufacturing stage) is the largest contributor to the climate change impact, owed to the activity of the rotary kiln, which emits CO_2 simultaneously due to fuel combustion and raw material decarbonation. The majority of carbon emissions have a fossil origin (over 93%), and less than 7% have a biogenic source.

6.2 IS scenarios

Four scenarios based on IS measures were created for a comparative study using the base LCI model as the reference and CEMBUREAU's 2030 targets as the object of study (Table 9). The 2030 roadmap targets were selected due its emphasis on applying readily available best available techniques (BATs) focusing on IS (CEMBUREAU 2020). Although the base LCIA considers all the core impact categories contemplated by EN 15804 + A2, the study will focus on climate change as it is the major environmental concern within the sector (CEMBUREAU 2020). The LCIA characterisation results obtained from running the inventory using the EN 15804 + A2 method on SimaPro is available in the supplementary material (Table 4).

6.3 Comparative LCIA results

Table 10 depicts the comparative LCIA results attained by applying the measures specified in Table 9 and by solely extracting the results for impacts on climate change. Results are shown divided across two subcategories of climate change (fossil and biogenic) in kg of CO_2-eq distributed between each life cycle stage. For each scenario and sub impact category, the modelled CO_2-eq reduction is also listed.

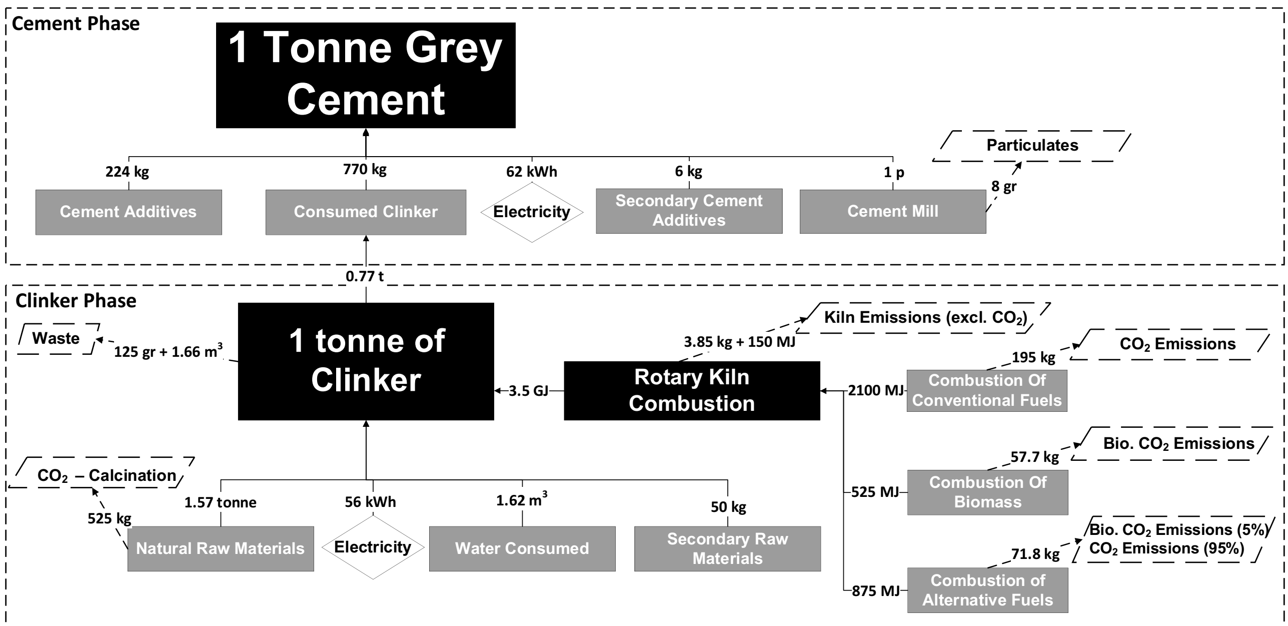


Fig. 7 Diagram of the LCA model structure for cement manufacturing in a typical European cement plant

6.4 Interpretation of results

6.4.1 Model validation

In order to interpret the results, there is a need to appraise the model quality by comparing the model LCIA results with published models available (ecoinvent 2020). The selected reference models are the results from the article of Moretti and Caro (2017) concerning a life cycle assessment of the Italian cement industry based on EN 15804 (Technical Committee CEN/TC 350 2013), and two unit processes from ecoinvent: 'Cement, Portland {Europe without Switzerland} | production | Cut-off, U' and 'Portland cement (CEM I), CEMBUREAU technology mix, CEMBUREAU production mix, at plant, EN 197–1 RER S' based on CEMBUREAU input (ecoinvent 2020).

Figure 8 illustrates the discrepancies in LCIA results of the three selected reference models compared to the author's model for the core categories of EN 15804 (Technical Committee CEN/TC 350 2013). Note that the model of Moretti and Caro (2017) agglomerates the eutrophication (EP) results and does not consider the water depletion potential (WDP) impact category; therefore, these are absent.

Differences are expected as each model is supported by various sources covering different periods, regions and even blends of cement. However, except a few indicators, the order of magnitude for most results is equivalent, and regarding the focal impact category (climate change), the difference in 'GWP – Total' is no larger than 25%.

The high gap between the 'GWP-biogenic' results is related with the selected fuel mix in the reference models. Moretti and Caro (2017) assumed, in its model, a calorific substitution by means of alternative fuels of 13% (5% biomass), whereas in the author's model, the substitution rate was 25% (15% biomass); consequently, the emission of biogenic carbon will naturally be higher. Additionally, the analysis of the inventory from the reference models extracted from ecoinvent shows that the difference is also due to a modest adoption of alternative fuels in the unit process (adoption of alternative fuels lower than 18%) (ecoinvent 2020). These divergences can be reasonably justified by the temporal coverage of each model, as the authors in this paper use newer data which possibly reflects recent efforts in the reduction of greenhouse gases (i.e. greater use of biomass). The selected electricity mix might also influence results,

Table 8 LCIA characterisation results, separated by the LCA stage

Impact indicator (unit: kg CO_2-eq)	Climate change-fossil	Climate change-biogenic	Climate change-total
Module A1	*47.4*	*0.1*	*48.2 (6.5%)**
Module A2	*11.4*	*0.01*	*11.5 (1.6%)**
Module A3	*630.0*	*47.5*	*677.6 (91.9%)**
Modules A1–A3	*688.9 (93.4%)***	*47.7 (6.5%)***	**737.3**

*Percentual contribution of each module to the total Climate Change results; ** Fossil and Biogenic percentual contribution towards the total Climate Change results

Table 9 Alternative scenarios to be used in the comparative study

Scenarios	Current situation, business as usual (BAU)	IS measures	Expected reduction (kg CO_2/tonne cement)
1. Alternative decarbonised raw materials[a]	5% decarbonised raw materials	↑11% decarbonised raw materials	– 14
2. Alternative fuels (including biomass)	25% waste-based 15% biomass	↑30% waste-based ↑30% biomass	– 30
3. Clinker substitution	77% clinker (0.6% clinker substitutes)	↓74% clinker (↑3.6% clinker substitutes)	– 24
4. 2030 IS measures	Cumulative	Cumulative	– 68

Source: CEMBUREAU (2020)

[a]The roadmap does not refer clearly any goal for integration of alternative decarbonised raw materials; however, it does refer to the expected 14 kg of CO_2 reduction (CEMBUREAU 2020). Inserting this reduction into the model to extract the amount of alternative raw materials reveals a 6% increase of decarbonised raw materials compared to BAU, from 5 to 11% in 2030 (CEMBUREAU 2020)

as the author's model is based on the 2018 Portuguese mix which has a higher renewable capacity than the European average (REN 2019; European Environment Agency 2021).

The very high discrepancies found on the indicators 'Eutrophication Potential-Freshwater' and 'Abiotic Depletion – Minerals & Metals' do not seem to be related to 'direct impacts' incurring from the cement manufacturing. But, it rather appears to be associated with the choice of background processes from ecoinvent (such as petcoke) whose characteristics can highly affect these indicators. The model developed in this paper was partially based on primary data from Portuguese cement plants which provides accurate results but can originate deviances motivated by regional characteristics. A more detailed view on the comparison is available in the supplementary material (Table 5).

6.4.2 Appraisal of IS scenarios

Figure 9 depicts the variation of CO_2-equivalent emissions for each established IS scenario in comparison with the base scenario. Results are divided into fossil, biogenic and cumulative emissions. The comparative LCIA demonstrate that IS measures based on CEMBUREAU's 2030 targets can contribute for an overall reduction in greenhouse gas emissions.

Scenario 1 and scenario 3 yield the most expressive reduction in CO_2-equivalent emissions, 15.9 kg and 23.3 kg,

Table 10 Comparison of climate change impact categories across the four established IS scenarios and the base scenario

Climate change impact (kg of CO_2-eq)	Fossil	Biogenic	Total
Scenario 1: decarbonised raw materials	673.0 ↓	47.7 =	721.3 ↓
Module A1	46.1 ↓	0.1 =	46.9 ↓
Module A2	12.7 ↑	0.01 =	12.7 ↑
Module A3	614.2 ↓	47.5 =	661.7 ↓
Reduction	– 15.9 (2.3%)	– 0.001 (0.0%)	– 15.9 (2.2%)
Scenario 2: alternative fuels	641.2 ↓↓	92.7 ↑↑	734.6 ↓
Module A1	45.9 ↓	0.1 =	46.7 ↓
Module A2	11.7 ↑	0.01 =	11.7 ↑
Module A3	583.6 ↓↓	92.6 ↑↑	676.1 ↓
Reduction	– 47.7 (7.4%)	+ 45.0 (– 48.6%)	– 2.7 (0.4%)
Scenario 3: clinker substitution	667.2 ↓	46.1 ↓	714.0 ↓
Module A1	50.0 ↑	0.4 ↑	51.1 ↑
Module A2	12.1 ↑	0.01 =	12.1 ↑
Module A3	605.2 ↓	45.7 ↓	650.8 ↓
Reduction	– 21.6 (3.2%)	– 1.6 (3.5%)	– 23.3 (3.3%)
Scenario 4: CEMBUREAU 2030	608.4 ↓↓	89.4 ↑↑	698.4 ↓
Module A1	34.1 ↓	0.4 ↑	35.1 ↓
Module A2	13.5 ↑	0.01 =	13.5 ↑
Module A3	560.8 ↓↓	89.0 ↑↑	649.8 ↓
Reduction	– 80.5 (13.2%)	+ 41.7 (– 46.7%)	– 38.9 (5.6%)

The symbols '↑', '↓' and '=' denote variations (increase, decrease, no variation) between the baseline and the four IS scenarios

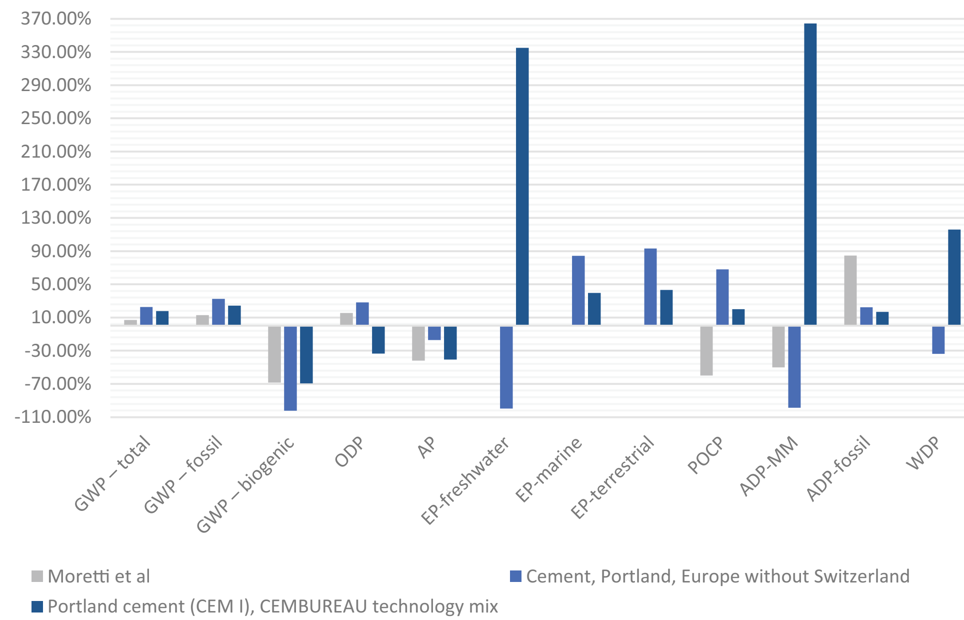


Fig. 8 LCIA results variation (in percentage) for three selected reference models against a baseline based on the author's model results. Impact categories based on EN 15804. Biogenic CO_2 was considered in 'GWP – total' for the author's model

respectively, per tonne of cement produced, demonstrating the effectiveness of the industrial synergy measures on reducing greenhouse gas emissions, particularly in the manufacturing stage. Results are consistent with expectations, as the usage of already decarbonised raw materials avoids calcination-derived emissions, and the reduction of clinker, the component responsible for the bulk embodied CO_2 emissions, evidently decreases the final product carbon footprint. A slight increase (~1%) in carbon emissions from freight transport to the factory gate is observed due to a higher dependency on externally sourced materials, yet its effect is negligible compared to the gains.

Regarding scenario 2, it does not produce the expected outcome, with a modest 2.7 kg decrease in total greenhouse gas emissions, a stark discrepancy compared with the literature. The result is a direct consequence of the chosen impact assessment method which is based on the revised EN 15804 standard (Technical Committee CEN/TC 350 2013). This unexpected outcome arises from the handling of biogenic carbon, and the *EN 15804 + A2* impact assessment method from SimaPro assumes that biogenic carbon produces the same effect as fossil carbon, but it could be neutralized if it is extracted from the atmosphere. Scenario 2 involves increasing the energetic contribution of alternative fuels from 40 to 60%, doubling the biomass contribution (from 15 to 30%), and an expressive increase in biogenic carbon emission offsetting the decrease in fossil carbon emissions is expected. As scenario concerns an activity within the rotary kiln, naturally, the mostly affected LCA stage is manufacturing (A3) with a considerable 47.7 kg of fossil CO_2 reduction by enhancing the intake of alternative fuels.

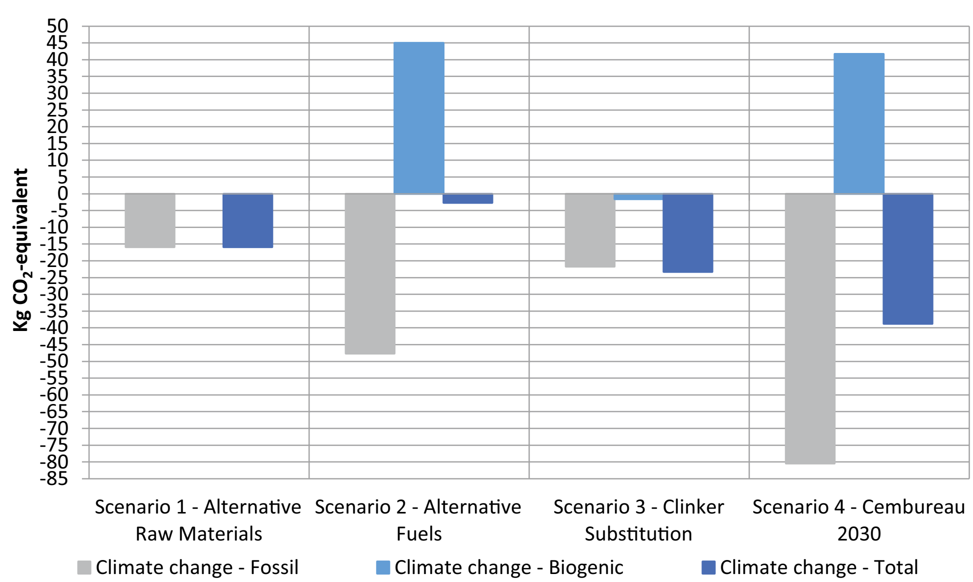


Fig. 9 Variation in CO_2-eq emissions for the established IS scenarios

Lastly, scenario 4 corresponds to the aggregate CEMBUREAU's IS measures and targets for 2030 in an individual scenario covering the use of waste-based raw materials, fuels and clinker substitutes. The scenario produced a substantial carbon footprint reduction of 38.9 kg of CO_2-equivalent (80 kg if biogenic carbon is disregarded). As anticipated, the reduction was most significant at the LCA stage with the highest contribution to climate change (−27.8 kg in module A3) as all IS measures mainly focus on enhancing the rotary kiln activity. The supply impact of raw materials decreased by 13.1 kg, and the climate change contribution from freight transport increased, albeit slightly by 2 kg, due to the higher demand for external materials, yet it does not have a substantial effect on the results.

The approach to biogenic carbon emissions is a controversial topic, and there is no consensus on how to approach such emissions. The neutrality principle states that biogenic emissions can be compensated by biomass sustainable regrowth in a relatively short term; thus, emissions from biomass fuels and the biogenic carbon content of mixed fuels should have a null climate change impact. In the author's opinion, such claim is flawed for the particular case of cement. Firstly, the impact from the supply of alternative fuels was assigned to the system that generates it being out of the LCA boundaries. Biomass growth, or any downstream carbon uptake, is outside of the cement product system (LCA stages A1–A3) and should not be accounted to avoid double counting. Secondly, the neutrality principle assumes that biomass must originate from a sustainable source to guarantee the offset by its growth; in the author's view, it is a dubious concept, being difficult to prove that the supplied fuels do originate from a sustainable origin. Moreover, an undisclosed percentage of the fuel classified as biomass might be animal-based (animal meal) whose source is non-carbon neutral. The authors reckon that the complete inventory approach would provide more accurate results when evaluating the environmental impact of an intermediary construction material such as cement.

The revised EN 15804 + A2 standard assumes this complete inventory approach which prompts a substantial repercussion in climate change impact assessment for the IS measure of alternative fuels when compared with a method that assumes the biogenic carbon neutrality. Using the EN 15804 + A2 method in scenario 2 would generate a 2.7 kg CO_2-eq decrease, whereas using *Environmental Footprint v3*, the reduction would surge to 47.1 kg. A visualisation of this effect is available in the supplementary information (Fig. 4). Depending on the chosen impact assessment method, the results can vary widely, and the authors of this paper recommend a careful selection of the method according to the desired output of the life cycle study. The following work will continue to adhere to the 'EN 15804 + A2 method' as it is a SimaPro approach to the standard; however, both approaches to biogenic emissions will be presented in the results.

IS-motivated GHG reduction hails from the avoidance of both calcination and combustion emissions through the replacement of primary materials and consumables with less carbon potent alternatives. Nevertheless, Fig. 10 reveals that in spite of prompting a reduction in GHG emissions, the sole implementation of IS measures contributes, but not sufficient, to resolve the cement sector environmental conundrum, providing a 5.6% decrease (12% if biogenic carbon is omitted). Even an ample replacement of fossil fuels with waste-based alternatives and biomass would not remove the necessity for a combustion reaction, and its corresponding environmental cost would not be nullified.

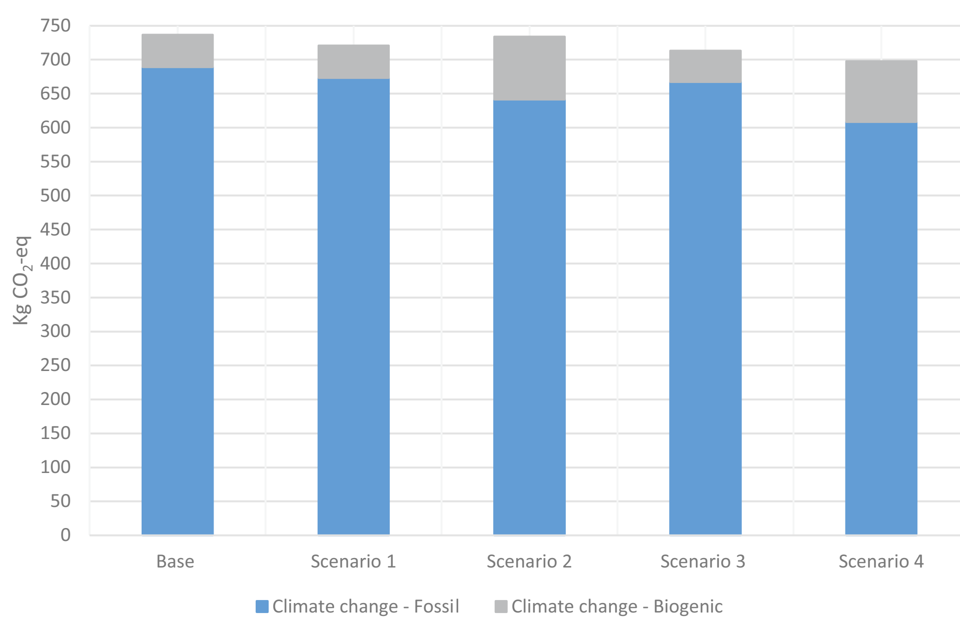


Fig. 10 Graphical comparison between the established IS scenarios and the baseline

Furthermore, over half a tonne of CO_2 is released per tonne of clinker manufactured due to calcination, while decarbonised raw materials soften this impact; to the current knowledge, it is difficult to increase the amount of alternative materials substantially or fully substitute clinker without affecting the properties of the final product. While IS measures provide a net positive contribute for GHG reduction and contribute for the economy circularity, to achieve zero net emissions by 2050, disruptive technologies such as carbon capture, utilization and storage (CCUS) are a key.

CCUS could open a door for new IS opportunities as the carbon captured from the kilns can be stored and deployed on other industrial sectors. The stored CO_2 could also be combined with green hydrogen to produce green methane that would be either re-introduced in the clinker kiln as fuel or injected to a gas distribution pipeline.

6.5 Analysis on the potential to achieve CEMBUREAU's 2030 objectives

Concerning CEMBUREAU's prospect for its 2030 targets, Table 11 compares its expectations for GHG reduction by implementing IS measures with the results from the LCIA study. One should note that CEMBUREAU solely tracks CO_2 emissions for its considerations, whereas the used LCIA method contemplates other GHG emissions (CEMBUREAU 2020).

The results show that scenario 1 produces a result in line with CEMBUREAU's prospects; however, this result is expected and should be disregarded for further interpretation, as the CO_2 reduction was extracted from CEMBUREAU's own expectations (the slight deviance arises from tertiary factors such as raw material supply). The evidence of interest extracted from scenario 1 is the amount of decarbonised raw materials necessary to achieve 2030 expectations, around 85 kg per tonne of cement, a 220% increase from BAU's 39 kg (CEMBUREAU 2020). Such decrease might be perceived as too ambitious, as sources from the Portuguese cement industry already referred difficulties in pretreating and selecting alternative raw materials so it does not damage manufacturing equipment or results in an inferior product.

In scenario 2, interpretation is subject to the handling of biogenic carbon, and current CEMBUREAU's roadmap does not specify the contribution of biogenic carbon for its calculations (CEMBUREAU 2020). Assuming that CEMBUREAU neglected the climate change effects of biogenic carbon, the LCIA would actually result in a better outlook, with CEMBUREAU expecting a 30 kg CO_2 reduction per tonne of cement, and the model suggesting a 47.4 kg reduction (CEMBUREAU 2020). However, if biogenic carbon is considered to contribute for climate change, CEMBUREAU's expectations would be considerably more optimistic than the LCIA result of a 2.7 kg CO_2 reduction per tonne of cement (CEMBUREAU 2020).

In scenario 3, LCIA results are mostly in line with CEMBUREAU's expectations. According to the model, clinker substitution produces a 23.3 kg of CO_2 reduction (21.1 kg if biogenic carbon is disregarded) which is reasonably close to the 24 kg expected by CEMBUREAU roadmap (CEMBUREAU 2020).

Lastly, scenario 4 corresponds to the combined implementation of the three previously mentioned IS measures according to CEMBUREAU's targets for 2030, with its roadmap attributing a 68 kg saving (CEMBUREAU 2020). Once more, depending on the approach to biogenic carbon, LCIA results can be either more optimistic, granting an 80 kg reduction if biogenic carbon is omitted, or having a less positive outlook with a 38.9 kg CO_2 decrease if the EN 15804 + A2 impact assessment method is considered.

The impact assessment was also performed with alternate impact assessment methods to strengthen the main conclusions (TRACI 2.1 and IPCC 2013 GWP 500a), and a similar result to the LCIA excluding the contribution of biogenic carbon was obtained, thus reconfirming the validity of the main conclusions. In addition, the alternate LCIA indicates that these impact assessment methods also do not consider the biogenic carbon contribution for climate change, which might potentially skew the interpretation of results and erroneously influence policymakers' decision-making.

We may argue that the deviance in comparison to CEMBUREAU's expectations is due to the differences in the LCI model used and the impact assessment methods that could have been chosen in a fashion that led to more desirable expectations (CEMBUREAU 2020).

Table 11 Difference between CEMBUREAU's expected CO_2 reduction and the LCIA of CO_2 in the model

Scenarios (unit: kg CO_2-eq/t cement)	Expected reduction	LCIA results	LCIA results (*Excl. Bio. C.*)	Alternate LCIA results	
				(*TRACI 2.1*)	(*IPCC 2013*)
1. Alternative raw materials	– 14	– 15.9	– 15.6	– 15.6	– 15.5
2. Alt. fuels (w/ biomass)	– 30	– 2.7	– 47.4	– 47.1	– 46.8
3. Clinker substitution	– 24	– 23.3	– 21.1	– 21.1	– 21.1
4. 2030 IS measures	– 68	– 38.9	– 80.0	– 79.8	– 79.5

Source: CEMBUREAU (2020)

7 Conclusions

The impact of the industrial symbiotic relationships of the European cement industry and the environmental impact derived from its implementation were justified. In a first stage, the concept of industrial synergy was explored as well as the options available for the cement manufacturing industry. In a subsequent section, a life cycle assessment study was carried out to evaluate the impact of IS measures and appraise the validity of the sector's environmental objectives for the year 2030, corresponding to the intermediate goals of carbon neutrality roadmap for 2050.

Results from the LCA study showed that IS implementation managed to produce a net positive impact, effectively reducing GHG emissions; albeit at a relatively smaller scale when comparing with the overall emissions from the kiln system, a 6% (12% assuming biogenic carbon neutrality) reduction was observed. However, the approach to biogenic carbon emissions posed a challenge, as the use (or omission) of these emissions affects the results substantially. As such, depending on the approach to biogenic carbon, CEMBUREAU's intermediate 2030 objectives for its 2050 Carbon Neutrality Roadmap are either overachieved or underachieved. The authors suggest having a follow-up work to be focused on studying the approach to biogenic carbon emissions in a LCA studies, as well as investigating the potential future pathways for industrial synergy through carbon capture, utilization and storage (CCUS) and use.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11367-023-02159-9.

Funding This research was partially funded by the c[5]Lab, Sustainable Construction Materials Association, through the POR Centro and POR Lisboa (CENTRO-04–3559-FSE-000096 and LISBOA-05-3559-FSE-000008, respectively).

Data availability Data sharing is not applicable to this article as no datasets were generated or analysed during the current study. All the data used was obtained from publicly available datasets.

Declarations

Conflict of interest The authors declare no competing interests.

References

3drivers - Engenharia Inovação e Ambiente; AVE - Gestão Ambiental e Valorização Energética SA (2018) 13 Anos De Coprocessamento Em Portugal

Aalborg Portland (2015) Annual Environmental Report 2015. Environment and Health & Safety

Adamides ED, Mouzakitis Y (2009) Industrial ecosystems as technological niches. J Clean Prod 17:172–180. https://doi.org/10.1016/j.jclepro.2008.04.003

Albino V, Fraccascia L (2015) The industrial symbiosis approach: a classification of business models. Procedia Environ Sci Eng Manag

Ali AAMM, Negm AM, Bady MF et al (2016) Environmental impact assessment of the Egyptian cement industry based on a life-cycle assessment approach: a comparative study between Egyptian and Swiss plants. Clean Technol Environ Policy. https://doi.org/10.1007/s10098-016-1096-0

Ammenberg J, Baas L, Eklund M et al (2015) Improving the CO_2 performance of cement, part III: the relevance of industrial symbiosis and how to measure its impact. J Clean Prod. https://doi.org/10.1016/j.jclepro.2014.01.086

Andrew RM (2018) Global CO_2 emissions from cement production. Earth Syst Sci Data. https://doi.org/10.5194/essd-10-195-2018

ATIC - Associação Técnica da Indústria do Cimento (2021) Roteiro para a Neutralidade Carbónica 2050

ATIC - Associação Técnica da Indústria do Cimento (2019) Sobre ATIC - Associação Cimento

Baas L, Boons F (2007) The introduction and dissemination of the industrial symbiosis projects in the Rotterdam Harbour and Industry Complex. Int J Environ Technol Manag

Baldassarre B, Schepers M, Bocken N et al (2019) Industrial symbiosis: towards a design process for eco-industrial clusters by integrating circular economy and industrial ecology perspectives. J Clean Prod 216:446–460. https://doi.org/10.1016/j.jclepro.2019.01.091

Blengini GA (2006) Life cycle assessment tools for sustainable development: case studies for the mining and construction industries in Italy and Portugal. Instituto Superior Técnico

Boix M, Montastruc L, Ramos M et al (2017) Benefits analysis of optimal design of eco-industrial parks through life cycle indicators. Comput Aided Chem Eng 40:1951–1956

Cantini A, Leoni L, De Carlo F et al (2021) Technological energy efficiency improvements in cement industries. Sustain. https://doi.org/10.3390/su13073810

CEMBUREAU (2013) The role of cement in the 2050 low carbon economy

CEMBUREAU (2020) Cementing the European Green Deal, reaching climate neutrality along the cement and concrete value chain by 2050. Eur Cem Assoc Brussels 1–38

Climate Technology Center Network (CTCN) (2011) Cement Sustainability Initiative (CSI). CO_2 and energy accounting and reporting standard for the cement industry. May 2011. In: The cement CO_2 and energy protocol

WBCSD Cement Sustainability Initiative (CSI) (2014) List of constants and default CO_2 emission factors. In: Cement CO_2 and energy protocol

Chertow MR (2000) Industrial symbiosis: literature and taxonomy. Annu Rev Energy Environ 25:313–337. https://doi.org/10.1146/annurev.energy.25.1.313

Chertow MR (2007) "Uncovering" industrial symbiosis. J Ind Ecol 11:11–30. https://doi.org/10.1162/jiec.2007.1110

CIMPOR (2018) Declaração Ambiental 2018 - Alhandra

Cruz Juarez RI, Finnegan S (2021) The environmental impact of cement production in Europe: a holistic review of existing EPDs. Clean Environ Syst 3:100053. https://doi.org/10.1016/j.cesys.2021.100053

Daddi T, Nucci B, Iraldo F (2017) Using life cycle assessment (LCA) to measure the environmental benefits of industrial symbiosis in an industrial cluster of SMEs. J Clean Prod. https://doi.org/10.1016/j.jclepro.2017.01.090

Deshpande S (2015) Development patterns and factors influencing the growth of industrial symbiosis

Deutz P, Lyons DI (2008) Editorial: Industrial symbiosis - an environmental perspective on regional development. Reg Stud

ecoinvent (2020) Ecoinvent database v3

European Commission (2019) The European Green Deal. Eur Comm. https://doi.org/10.1017/CBO9781107415324.004

European Comission (2021) Environmental Footprint v3

European Commission (2013) Best available techniques (BAT) reference document for the production of cement, lime and magnesium oxide

European Environment Agency (2021) Greenhouse gas emission intensity of electricity generation in Europe

Feiz R, Ammenberg J, Baas L et al (2015) Improving the CO_2 performance of cement, part I: utilizing life-cycle assessment and key performance indicators to assess development within the cement industry. J Clean Prod. https://doi.org/10.1016/j.jclepro.2014.01.083

García-Gusano D, Herrera I, Garraín D et al (2015) Life cycle assessment of the Spanish cement industry: implementation of environmental-friendly solutions. Clean Technol Environ Policy. https://doi.org/10.1007/s10098-014-0757-0

Geocycle (2018) The geocycle circular economy approach. https://www.geocycle.com/poland?address=Poland. Accessed 6 May 2020

Gesch MS (2015) Einsatz alternativer Rohstoffe im Zementherstellungsprozess - Hinter-grundwissen, technische Möglichkeiten und Handlungsempfehlungen

Gibbs D (2008) Industrial symbiosis and eco-industrial development: an introduction. Geogr Compass. https://doi.org/10.1111/j.1749-8198.2008.00123.x

Haberl H, Sprinz D, Bonazountas M et al (2012) Correcting a fundamental error in greenhouse gas accounting related to bioenergy. Energy Policy 45:18–23. https://doi.org/10.1016/j.enpol.2012.02.051

Haq H, Välisuo P, Niemi S (2021) Modelling sustainable industrial symbiosis. Energies. https://doi.org/10.3390/en14041172

Harris S (2004) Drivers and barriers to industrial ecology in the UK

Hashimoto S, Fujita T, Geng Y, Nagasawa E (2010) Realizing CO_2 emission reduction through industrial symbiosis: a cement production case study for Kawasaki. Resour Conserv Recycl. https://doi.org/10.1016/j.resconrec.2009.11.013

Henriques J, Ferrão P, Castro R, Azevedo J (2021) Industrial symbiosis: a sectoral analysis on enablers and barriers. Sustainability. https://doi.org/10.3390/su13041723

Institut Cerdà (2017) Reciclado y valorización de residuos en la industria cementera en España

Ismail Y (2020) Potential benefit of industrial symbiosis using life cycle assessment. J Phys Conf Ser

ISO (International Organization for Standardization) (2004) Environmental management — life cycle assessment — principles and framework (ISO 14040:2006). Environ Manag Syst Requir 44

Jacobsen NB (2006) Industrial symbiosis in Kalundborg, Denmark: a quantitative assessment of economic and environmental aspects. J Ind Ecol 10:239–255. https://doi.org/10.1162/108819806775545411

Lafarge Holcim Austria (2015) LafargeHolcim Austria: thinking circular about construction and demolition waste. https://www.lafargeholcim.com/austria-construction-waste-recycling. Accessed 6 May 2020

Liu Q, Jiang P, Zhao J et al (2011) Life cycle assessment of an industrial symbiosis based on energy recovery from dried sludge and used oil. J Clean Prod. https://doi.org/10.1016/j.jclepro.2011.06.013

Lombardi DR, Laybourn P (2012) Redefining industrial symbiosis. J Ind Ecol. https://doi.org/10.1111/j.1530-9290.2011.00444.x

Martin M, Harris S (2018) Prospecting the sustainability implications of an emerging industrial symbiosis network. Resour Conserv Recycl. https://doi.org/10.1016/j.resconrec.2018.07.026

Morales ME, Diemer A (2019) Industrial symbiosis dynamics, a strategy to accomplish complex analysis: the Dunkirk case study. Sustain. https://doi.org/10.3390/su11071971

Moretti L, Caro S (2017) Critical analysis of the life cycle assessment of the Italian cement industry. J Clean Prod 152:198–210. https://doi.org/10.1016/j.jclepro.2017.03.136

Notarnicola B, Tassielli G, Renzulli PA (2016) Industrial symbiosis in the Taranto industrial district: current level, constraints and potential new synergies. J Clean Prod. https://doi.org/10.1016/j.jclepro.2016.02.056

NRMCA (2008) Concrete CO_2 fact sheet. National Ready Mixed Concrete Association

O.C.O Technology (2010) M-LS by O.C.O Technology: a carbon-negative limestone aggregate created with residues from waste to energy residue

Patrício J, Costa I, Niza S (2015) Urban material cycle closing - assessment of industrial waste management in Lisbon region. J Clean Prod

Quintana J (2019) Scaler Deliverable 3.4: synergies socio-economic impact assessment

Rebitzer G, Ekvall T, Frischknecht R et al (2004) Life cycle assessment. Part 1: framework, goal and scope definition, inventory analysis, and applications. Environ Int 30:701–720. https://doi.org/10.1016/j.envint.2003.11.005

REN (2019) Diagrama de Carga 2018

SECIL (2018) Declaração Ambiental 2018. SECIL-OUTÃO 2018

Short SW, Bocken NMP, Barlow CY, Chertow MR (2014a) From refining sugar to growing tomatoes: industrial ecology and business model evolution. J Ind Ecol. https://doi.org/10.1111/jiec.12171

Short SW, Bocken NMP, Barlow CY, Chertow MR (2014b) From refining sugar to growing tomatoes. J Ind Ecol 18:603–618. https://doi.org/10.1111/jiec.12171

Soyez K, Graßl H (2008) Climate change and technological options: basic facts, evaluation and practical solutions

Stéphane O, Jean-Baptiste Q, Charles-Xavier S et al (2019) A cross-sectorial synergies identification methodology for industrial symbiosis. In: Smart Innovation, Systems and Technologies. Springer Singapore, pp 229–240

Technical Committee CEN/TC 350 (2013) EN 15804:2012+A2 - sustainability of construction works - environmental product declarations - core rules for the product category of construction products

Valderrama C, Granados R, Cortina JL et al (2012) Implementation of best available techniques in cement manufacturing: a life-cycle assessment study. J Clean Prod. https://doi.org/10.1016/j.jclepro.2011.11.055

Vladimirova D, Miller K, Evans S (2018) Scaler Deliverable 2.1: lessons learn and best practices for enhancing industrial symbiosis in the process industry

Wiloso EI, Heijungs R, Huppes G, Fang K (2016) Effect of biogenic carbon inventory on the life cycle assessment of bioenergy: challenges to the neutrality assumption J. Clean Prod 125:78–85. https://doi.org/10.1016/j.jclepro.2016.03.096

Yu F, Han F, Cui Z (2015) Assessment of life cycle environmental benefits of an industrial symbiosis cluster in China. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-014-3712-z

Zhang Y, Zheng H, Chen B, Yang N (2013) Social network analysis and network connectedness analysis for industrial symbiotic systems: model development and case study. Front Earth Sci 7:169–181. https://doi.org/10.1007/s11707-012-0349-4

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