Consequential life cycle assessment of Brazilian cement industry technology projections for 2050

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Abstract. In the upcoming decades, cement production growth is expected to exceed the increase in availability of clinker substitutes. Increased clinker replacement rates in cement and use of alternatives fuels were pointed out as the main alternatives for reducing emissions of the national cement industry, whilst increasing cement production in 2050. Consequential life cycle assessment (CLCA) offers a framework to capture environmental consequences from demand alterations. Modelling the cement production and markets involved is however challenging, given conceptual (only unconstrained markets are considered) and practical modelling limitations (e.g. model granularity compatible with CLCA interests). This paper refers to an ongoing work and adopts a two-stage approach to discuss the effects of the change on the average cement production process in Brazil. We first performed a CLCA without formal affected market identification to estimate the potential environmental impacts of the technology change proposed in the Brazilian Cement Technology Roadmap. Secondly, we used a Computable General Equilibrium (CGE) Model of the Brazilian economy to (more) realistically foresee short-term effects induced by such change. The CGE model comprises 102 economic activities, including cement production and its production chain. Our results indicate that (i) increasing the proportion of calcined clay and limestone filler as clinker partial substitutes and (ii) excluding charcoal from the fuel mix composition at the kiln would impact all economic sectors. Our preliminary findings suggest that the increased efficiency in cement production would create some rebound effect that would not invalidate the emission benefits from displacing energy and virgin materials. Additional impact categories and consequences in other economic sectors should be further investigated.

1. Introduction
The recovery of the Brazilian economy from its current recession, and subsequent GDP growth plus the infrastructure and housing deficit should drive up cement demand steadily from 2020 to 2040. According to the Cement Technology Roadmap for Brazil [1], the production is expected to reach its peak in 2045, should it follow a high- (170Mt) or a low-demand variant (127 Mt), considered more realistic. Such long-term growth poses a considerable challenge to the Brazilian cement sector in terms of energy demand and CO₂ emissions.
The cement manufacturing industry is one of the five most energy intensive sectors in the world. Typically, 30% to 40% of the direct CO₂ emissions result from burning a mix of fuels, whilst 60% to 70% are produced by the chemical reaction that converts limestone into calcium oxide (calcination) to form Portland clinker. Additional indirect 5% of CO₂ emissions result from electrical consumption by the industrial plant. Whilst the calcination contribution (63%) and the burning of fuels (36%) are within world average emission ranges, indirect emission from electricity consumption in Brazil is only about 1%, due to its distinguished, highly renewable (>70%), electricity matrix.

In 2014, the Brazilian cement industry utilized 1.5 million tons of waste (8%) and biomass (7%). At the current level of thermal substitution, the remaining 85% of the fuel mix is fossil-based, mostly petroleum coke (pet coke). These figures show potential for increased use of biomass and waste - including municipal solid waste - as fuel, given the favorable characteristics cement kilns offer to coprocessing - i.e. combined operation of manufacturing cement together with the burning of waste – favoring impact reduction from otherwise inadequate disposal of waste in nature [1].

Simulated contribution of non-renewable fossil fuels in cement production could diminish from 85% to 45%, due to increased share of waste and biomass in the fuel mix. Decrease in the projected thermal and electrical intensity would become more noticeable after replacement of obsolete equipment by 2030 and reach 3.2 GJ/t of clinker (92 kWh/t of cement) by 2050 [1].

The Brazilian raw material has higher magnesium carbonate content and, therefore, higher calcination factor than the world average. Still, the Brazilian cement industry has one of the lowest specific CO₂ emission levels in the world, due to mitigation actions implemented over recent decades, such as use of alternative fuels and clinker substitutes. Blast furnace slag (bfs) and fly ash have been used as additives to Portland cement for decades.

In 2014, more than 95% of granulated bfs produced in the country was consumed by the cement industry [1]. However, increased use of bfs by the cement industry is challenged, in the short and medium term, by the lower growth in supply in relation to the increase in cement production, due to the rising global competition faced by the national steel industry; and in the long term by the evolution of technological processes, with a lower production of slag per ton of pig iron produced. Fly ash shows a similar trend, due to lower investments in coal-burning thermoelectric plants, decarbonization of the Brazilian electric grid, and low utilization factor of thermoelectric plants, which was around 50% in 2013 [1].

Considering the constrained supply of the major clinker substitutes used today (bfs and fly ash) and the increased demand for cement in the long run, the Roadmap BR projected decreases in the clinker factor (proportion clinker/cement) based on increased proportions of limestone filler and calcined clay as clinker alternatives. Practical implementation of such measures still faces technical, economic and legislative limitations created by e.g. different applications of the final product, environmental regulations and technical standards, local availability of raw materials, logistics complexity and costs, contractual difficulties to ensure waste supply, and challenging performance (calorific power, high moisture and concentration of chlorine or other detrimental substances) [1]. Nevertheless, these assumptions formed the basis of our assessment.

Consequential LCA (CLCA) modelling aims at identifying the study boundaries to encompass likely consequences of an action or decision [3]. While attributional life cycle assessment focuses on describing the environmentally relevant impacts of the activities that contribute to a specific property of a product or process, consequential assessment describes how environmentally relevant impacts will, or could, change in response to the studied action or decision [5]. Attributional and consequential modelling are therefore intended to answer different questions [3]. Attributional LCI aims at answering “how are environmentally relevant things (pollutants, resources, and exchanges among processes) flowing within the chosen temporal window?” whereas Consequential LCI aims at answering “how will flows change in response to decisions?” [6].

Ultimately, the differences between attributional and consequential LCA are the result of the choices made in the Goal and Scope Definition phase of the general LCA process [5]. In order to
incorporate possible consequences, CLCA models include additional economic data like marginal production costs, elasticity of supply and demand etc [4].

In CLCA, the system boundaries are defined to include the activities that change as a consequence of a small change in the demand for the studied products. To understand the potential consequences of a decision that involves the substitution of one product with another, the differences between the alternative product systems - that have the same output, fulfil the same performance requirements, i.e., have the same functional unit - are modelled [5]. Prox and Curran [5] explain the step-wise procedure originally proposed by Weidema et al. [7], which consists of: Step 1 – describing the product by its properties; Step 2 – identifying market boundaries; Step 3 – identifying product alternatives; Step 4 – defining the functional unit; and Step 5 – determining reference flows for alternatives.

The functional unit is the service delivered by the product system (i.e. it represents the meeting of the demand for an additional unit of the product under study), which provides a reference for inputs and outputs to be related. The choice of functional unit should reflect the quantity, properties, and duration of the product/service of interest. And ensure same functionality for the alternatives compared. Where it represents the meeting of the demand for an additional unit of the product under study, the functional unit does not displace any marginal product [2].

The system boundary definition determines which processes are to be included (or not) in the assessment. CLCA only considers ‘unconstrained markets’, that is, those represented by determining products. A determining product is defined as a product for which demand is directly linked to its production. Contrastingly, a co-product is said to be dependent when demand for it has no influence on its production. Such ‘constrained markets’ are excluded from the CLCA system boundary. Also, CLCA should only include the activities that change as a response to an additional demand for the functional unit, and the corresponding marginal effects, i.e. the effects that take place in addition to what would have happened without an increased demand for the functional unit (ceteris paribus principle), displacing e.g. marginal virgin materials and energy flows [2].

This paper aims at assessing the environmental consequences of the proposed change for the cement production technology in Brazil, by identifying the reference flows for alternative energy and virgin materials whilst offering wider consideration of reflections on other productive sectors. Our baseline was the production system in 2014, modified by incorporating fuel mix and cement composition projected by the Roadmap BR for 2050.

2. Method
We followed a two-stage approach to discuss the effects of the change on the average cement production process in Brazil. We first perform a CLCA without formal affected market identification to estimate the potential environmental impacts of the predicted change by solely using data published in the Roadmap BR [1]. Secondly, we used a general equilibrium model of the Brazilian economy (Section 2.5) to (more) realistically foresee which short-term effects are induced by this change.

Our CLCA was conducted following the ISO standards. First, the goal and scope of the study are outlined, to set the context for the study and ensure that the outcome is consistent with its objectives. The adopted functional unit provides a reference for inputs and outputs to be related. The corresponding system boundary is described separately below. SimaPro 8.5 supported the assessment. The inventory that reflects the studied system is composed by primary data for the clinker production (foreground), and secondary data from the Ecoinvent v3.4 database adapted to the Brazilian energy mix (background). Finally, the environmental implications were reviewed in the impact assessment step using CML-IA baseline v3.05, and the results were interpreted and iteratively revised.

The goal of our CLCA was to estimate the potential environmental impacts of the decision to implement two major technology changes in the Brazilian cement production process projected for 2050 described in the Roadmap BR [1]: change in cement composition (route 1) and change in the fuel mix used (technology route 2), relatively to cement production as per 2014 (baseline).

Key to defining the scope of CLCA is an endeavour to foresee what changes are induced by implementing the decision under assessment. The geographical scope of this assessment is Brazil, which
defines the related legislative, political, and market contexts important to determine the marginal processes and technologies affected by the changes in demand analysed. The technological scope refers to cement production as per 2014 (baseline) and the same production capacity but after the technology changes considered. The temporal scope of the assessment is 2014-2050. Long term, investment-intensive route 3 (carbon capture and utilization or storage - CCUS) is not included in this study. Therefore, the time horizon refers to short term marginal effects (‘operational margin’). This means that existing capacity can absorb the shocks of changes in demand for the functional unit and only changes in the utilization of existing production capacity are considered.

Table 1 summarizes characteristics of clinker and cement production as per 2014 (baseline) and after technology changes projected for 2050.

| 1 t of (average) cement 2014 (baseline) | 1 t of (average) cement 2050 |
|----------------------------------------|----------------------------|
| **Inputs**                             | **Inputs**                 |
| 3,5% gypsum                            | 3,5% gypsum                |
| 1% other                               | 2% other (+1%)             |
| 14% ggbs (dependent)                   | 11% ggbs (-3%) (dependent) |
| 3% fly ash (dependent)                 | 2,3% fly ash (-0,7%) (dependent) |
| 3% calcined clay (determining)         | 4% calcined clay (+1%) (determining) |
| 8% limestone filler (determining)      | 25% limestone filler (+17%) (determining) |
| 68% clinker (determining)              | 52% clinker (-16%) (determining) |
| **Fuel mix clinker (3,5 GJ)**          | **Fuel mix clinker (3,22 GJ)** |
| 6% charcoal (determining)              | 0 charcoal (-0,21 GJ) (determining) |
| 85% petcoke (dependent)                | 45% petcoke (-40%) (dependent) |
| 0,7% agricultural waste (dependent)    | 3,7% agricultural waste (+3%) (dependent) |
| 4,6% scrap tires (dependent)           | 5,1% scrap tires (+0,5%) (dependent) |
| 3,5% industrial blend waste (dependent)| 4% industrial blend waste (+0,5%) (dependent) |
|                                        | 7,4% sewage sludge (+7,4%) (dependent) |
|                                        | 17,4% non-hazardous waste (+17,4%) (dependent) |
|                                        | 17,3% municipal solid waste (+17,3%) (dependent) |
| 113 kWh average electricity demand     | 92 kWh average electricity demand (-21 kWh) |

The defined functional unit for this study is 1 ton of (average) Roadmap BR cement technology projected for 2050. Figure 1 shows the CLCA System boundary used in this study. Only determining products from the fuel mix (charcoal) and from the clinker substitute palette (limestone and clay) were computed within the system boundary. Displaced virgin materials refer to flows suppressed by increased shares of calcined clay and limestone filler to reduce clinker content. Displaced energy and electricity refer to the removal of charcoal from the fuel mix and increased technology efficiency in cement manufacturing.
2.1. Economic modelling

A Computable General Equilibrium (CGE) model enables to capture the consequences that a technological change from one single sector has on the output level of all other sectors of a given economy. For didactic purposes, Figure 2 illustrates a simplified (two-sector) economy according with the CGE model used in this paper.

In the domestic economy, the production level (XDj) of each sector (j) will combine an aggregate of inputs from the intermediate consumption (IC, e.g. X_{11} and X_{21} for sector 1, in Figure 2) with value added (VA) through a Leontief function, which requires inputs in constant proportions. The value added (VA) in each sector combines the capital (Kj) and labor (Lj) factors through a Constant Elasticity of Substitution (CES) function, which allows the substitution between the capital (Kj) and labor (Lj) factors whenever their relative prices change; whilst the intermediate consumption (IC) from a sector (j) refers to the use of inputs in a constant proportion (Leontief Function) and each of these inputs is in its turn a combination of domestic (XDDj) and imported (Mj) inputs.

The proportion of the production level (XDj) that stays in the domestic market (XDDj) or is exported (Ej) is defined by a ‘constant elasticity of transformation’ (CET) function, which considers the changes in the product’s relative prices in the international and domestic markets. The domestic production of product j (XDDj) is then combined with that product imports (Mj) through an Armington function, which considers the product’s relative prices in the domestic and international markets. The resulting sector supply of product j in the domestic economy (Xj) feeds the intermediate consumption (IC) and the final demand (FD), the latter composed of household consumption (C), government consumption (GC) and investments (I), essentially in civil construction and capital goods.
Figure 2 – CGE model used in this study illustrated for a two-sector economy. Blue boxes represent the products and services’ intermediated consumed (IC). Green boxes show the primary production factors: labor ($L_j$), capital ($K_j$), the elements of VA, the value added. Production (CES, Leontief and Armington) and transformation (CET) functions are shown in the white boxes. The brown boxes stand for the sector supply of products: $X_j$ is the supply in the domestic economy, composed of the product’s domestic market, $X_{DDj}$ (production level $XD_j$ minus exports $E_j$), and its imported share, $M_j$. Finally, the yellow boxes consist on the final demand products of the economy: $E_j$ is the exported proportion of the product; $C_j$ and $GC_j$ are respectively the household and the government consumption; and $I_j$ represents the investments.

This CGE model is built upon some classical assumptions: (i) the supply of each good and each factor of production (capital and labor) is equal to its demand - clear markets; (ii) each activity operates at zero economic profit (each sector operates in a perfect competition market, such that one sector’s revenues are equal to all of its costs, including remuneration over the capital factor); (iii) families maximize their utility in the consumption of goods, subject to the restriction of their income subtracted from their savings; (iv) firms seek to minimize their cost for a given level of production, subject to their technological constraints; (v) the government spends its revenue (taxes collection) on the provision of public services, social security expenditures and savings formation; (vi) it is assumed that all investment is financed by savings; (vii) savings are made up of external savings from government and households; (viii) external saving is given by the inverse of the trade balance, which is the difference between exports and imports.

The functions of demand for capital and labor in each sector of the domestic economy derive from the CES function that combines these two factors to result in value added. For each product, the demand function of household consumption results from the utility function LES (Linear Expenditure System). The investment demand function for each product is a Cobb-Douglas type, in which the share of expenses with each product is constant. Finally, the supply of public services results also from a Cobb-Douglas function: in this case, spending on each service is constant relative to government’s collection.

The database used in the CGE model refers to the Brazilian National Accounts [9] for the baseline
year (2014). An Input-Output Matrix was estimated from the National Accounts data using the method proposed by [8]. A 102-sector input matrix was then derived to determine the intermediate consumption. For this paper purposes, it was necessary to disaggregate the sectors of cement, clay and limestone production. Information for these activities were obtained from National Union of the Cement Industry – SNIC, and the Annual Industrial Production published by the Brazilian Institute of Geography and Statistics – IBGE [10].

3. Results and discussion

3.1. CLCA outcomes

To estimate the changes in material and energy flows resulting from the proposed technology changes in cement production, the environmental impacts were calculated relatively to the reference unit – 1 t of cement (modified technology), as shown in Table 2.

| Ecoinvent Dataset/Process modified | Quantity | Unit |
|-----------------------------------|----------|------|
| Clinker {RoW} | production | Conseq, U | -1,60E-01 | t |
| Charcoal {GLO} | production | Conseq, U | -1,46E-03 | t |
| Electricity, medium voltage {BR} | market for | Conseq, U | -2,10E+01 | kWh |
| Limestone, crushed, for mill {RoW} | production | Conseq, U | +1,70E-01 | t |
| Calcined clay | | | +1,00E-02 | t |

The amount of clinker substituted (i.e. avoided) and corresponding quantities of its substitutes – limestone filler and calcined clay – were defined by the cement production changes proposed by the Roadmap BR [1], as indicated in the CLCA system boundary (Figure 1). The modified manufacturing process is more energy-efficient, due to combined decrease in electricity demand (from 113 to 92 kWh/t cement) and in thermal needs. No prospective scenarios regarding alterations on the Brazilian electricity grid until 2050 were predicted. In view of CLCA methodology, charcoal was the only thermal energy source analysed. Of the total 0.28 GJ reduction, 0.21 GJ result from suppressing charcoal from the fuel mix. Its corresponding mass is presented based on a calorific value of 23 MJ/kg.

The datasets used were minimally modified for adherence to the Brazilian reality; hence, electricity and water inputs were altered to Brazilian data. Clinker and calcined clay production datasets were formulated using Brazilian average information, incorporated in novel datasets already delivered to Ecoinvent and to be published in version 3.6. The cement composition proportions used in the dataset (and actual displaced materials) refer to collected data in 2017 for Portland cement CP V – similar to European CEM I, whereas the Roadmap BR used weighted average of all produced cement types. This will be refined as this work progresses.

Results for the CLCA are presented in Figure 3 for different impact categories. The substitution of clinker reduces environmental burdens due to materials involved in its composition and energy required in process such as calcination, grinding and mixing. Incorporating limestone filler and calcined clay as substitutes indeed adds in impacts, but the net impact in each category is always reduced.
3.2. Affected sectors and changes in production levels

From the equilibrium observed for the Brazilian economy of 2014, in the CGE model, exogenous changes were made in the participation of clay, limestone and charcoal in the cement production, consistently with Table 1. These changes lead to a new economic equilibrium captured by the model. The industry-proposed changes modelled for cement production technology would enhance its economic efficiency and reduce cement’s production cost, which would in turn reduce the product’s price, and ultimately increase its demand and production. The technological change in the cement sector trigger changes in prices and ultimately in the production levels of all 102 sectors of the economy. For simplicity, Table 3 list is truncated to show only the sectors with the highest increments or reductions in production level.

Table 3 - Sectors with the highest production level increments or reductions after applying the cement technology change

| Sector                                | Change in production level |
|---------------------------------------|----------------------------|
| Cement                                | +0.0714%                   |
| Pulp and Mechanical Pulp Manufacturing| +0.0268%                   |
| Construction                          | +0.0233%                   |
| Other non-metallic mineral products   | +0.0227%                   |
| Paints, varnishes, enamels and lacquers| +0.0119%                   |
| Manufacture of petrochemical Diesel   | -0.0046%                   |
| Clay                                  | -0.0310%                   |
| Pesticides                            | -0.0445%                   |
| Fertilizers                           | -0.0457%                   |
| Forestry                              | -1.1324%                   |

The economic model assumes that inputs are used in constant proportions. Therefore, the additional demand for cement propagates activity increments across 81 economic sectors, whilst the remaining 20 sectors would reduce activity. The cement sector obviously shows the highest increase in production for being directly affected by its cost reduction, but it also directly stimulates e.g. production in the pulp
manufacturing (paper bags) and the construction sectors, besides the general increase in the whole economic activity. The highest reduction in the forestry sector production level stems from the suppression of charcoal as a thermal energy source in the revised cement production technology. Fertilizers and pesticides demand decrease accordingly. Reduction in clay production level consistently reflects the decreased flow of clay and slightly increased activity in the limestone sector (+0.00141%) in the revised cement composition.

Due to the cement cost matrix, the reduction of clay (overall input mass balance ~ -15%) and increase of limestone (overall input mass balance ~ +1%) reduced input costs by about 1.91%. The cost reduction reduces the cement price, which allows for the reported increase in demand and consequently in production. As the share of limestone in the cost of cement is much higher than that of clay, reduced expenditure on inputs affected proportionally little the final cement price. The emission balance would be positive but, from the economic perspective, the 0.07% increase in cement sector activity depicts a rebound effect, that is an increase in production level (and corresponding emissions and impacts) resulting from a technology change envisioned to decrease specific emissions (per t). This aspect shall be further investigated and characterized.

4. Final remarks
This simplified consequential LCA performed were based on the predictions brought forth by the Cement Production Roadmap Brazil, and showed that the two possible routes for impact minimization do not backfire: not only is the carbon intensity within the sector significantly reduced, all other assessed impact categories presented net reductions of at least 80%. The global equilibrium model, on its turn, showed that all 102 economic sectors are quantitatively affected by the predicted changes, with marginal increased or decreased production levels. We are currently working on the integration of the equilibrium model output with LCA tools to quantify the mentioned difference.

As with any LCAs in countries lacking a national inventory, our study was sometimes hindered by the absence of representative data. We attempted to limit this issue with dataset adaptation to best represent the national production scenario. Moreover, no prospective modelling of the electricity grid in 2050 was assessed. With the current worldwide trend to decarbonize electricity mixes, one could argue that the avoided impact in the next decades would be lower. Still, for GWP, the major benefit comes from clinker reduction, so conclusions would not have been deeply altered from a GHG emissions perspective.

Consequential LCAs are usually coupled with the step-wise procedure approach to identify the markets affected by a predicted change in demand, as briefly discussed in section 1. Our modelling relied on predictions already developed by the cited technology roadmap, assuming composition changes (and their quantities) according to specific sectorial information. These approaches involve subjective assumptions but facilitate the exploration of CLCA’s more sophisticated concept without increasing data collection complexity. The ease of application is however hindered by a biased perception of the economic sector’s response. Our paper, albeit only exploring the output of an equilibrium model without its full connection to LCA modelling, already shows how the demand change unfolds into the whole Brazilian economy. This is an ongoing work and additional impact categories and consequences in other economic sectors will be further investigated.

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