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Insight from computable general equilibrium model to consequential LCA of Brazilian cement production in 2050

ACV consequencial da produção de cimento brasileira em 2050 informada por modelo de equilíbrio geral computável

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Resumo

O Roadmap Tecnológico do Cimento Brasileiro propõe intensificar o emprego de substitutos de clínquer e combustíveis alternativos para reduzir as emissões de GEE até 2050. A avaliação consequencial do ciclo de vida estima potenciais implicações ambientais de uma mudança hipotética, ainda que apresente limitações no caso do cimento. Realizamos uma ACV usando dados do Roadmap, ignorando mercados restritos, depois previmos efeitos induzidos em outros setores da economia brasileira em 2050 usando um modelo de equilíbrio geral

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computável. As emissões da indústria de cimento aumentariam ligeiramente, mas as emissões totais de GEE diminuiriam em 941 Gg CO_{2eq}.

Palavras-chave: ACV consequencial. Modelo de equilíbrio geral computável. Produção de cimento. Brasil.

Abstract

The Brazilian Cement Technological Roadmap proposes intensified use of clinker substitutes and alternative fuels to reduce the sector's GHG emissions by 2050. Consequential life cycle assessment is valuable for estimating potential environmental consequences of a given change or strategy yet limited in the manufacturing context at hand. We performed an LCA using Roadmap data, ignoring restricted markets, then predicted short-term effects induced on other sectors of the Brazilian economy in 2050 using a computable general equilibrium (CGE) model. Cement industry's emissions would slightly increase, without escalating those of other economic sectors. Overall, GHG emissions would drop by 941 Gg CO_{2eq}.

Keywords: Consequential LCA. Computable general equilibrium model. Cement production. Brazil.

INTRODUCTION

Cement consumption is inherently connected with concerns related to the environmental consequences of its manufacturing. Replicating the global Cement Technology Roadmap effort, the Brazilian cement industry was recently mapped out and used as a baseline for outlining future trends for the industry, hereafter referred to as 'Roadmap BR'. The Roadmap BR [1] predicts that the national production of cement would reach its peak in 2045. If the current manufacturing model is maintained, increased production would be coupled with proportional increase in energy demand and in greenhouse gas (GHG) emissions, which represents a considerable challenge for the industry in terms of containing its environmental impacts.

The Roadmap BR recommendation aims to reduce the carbon intensity in domestic cement production by one third until 2050 – i.e., from 0.56 tCO_2/t cement (baseline 2014) to 0.38 tCO_2/t cement – to limit the increase in global temperature in the long term to 2°C [1]. The two main potential fronts to enable such reduction would be (a) increasing clinker substitution in cement and (b) the use of alternative fuels, which could lead to, respectively, 69% and 13% reduction of cumulative mitigation of CO_2 emissions within the considered time horizon [1].

Clinker replacement relies on mineral additions. However, the Roadmap BR also expects growth in cement production in the coming decades to outpace the availability of traditional clinker substitutes, such as ground granulated blast furnace slag (ggbs) and fly ash. In 2014, the cement industry consumed over 95% of the granulated slag produced in the country [1]. Given the limited growth of ggbs supply in the short and medium term, two types of additions tend to support decreased clinker/cement factor: limestone filler and, to a lesser extent, calcined clay.

For the estimated 13% of the reduction potential (55 Mt of CO_2), the second technology change proposal increases the proportion of alternative energy sources from 15% (2014 baseline) to 55% in 2050. Municipal Solid Waste (17% substitution) and Non-Hazardous Solid Waste (another 17%), both with high biomass content in their composition, represent the most suitable alternative sources for substituting fossil fuels currently used.

In view of the different potential technological routes that could lead to more sustainable industrial practices, traditional – or “attributional”- life cycle assessment (LCA) has emerged as a powerful tool for estimating environmental impacts of choices permeating decision-making processes. A variation within the LCA palette, consequential LCA (CLCA) represents the convergence of LCA and economic modelling methods [2] and aims to capture the environmental impacts of product systems that go beyond the physical relationships accounted for in attributional LCAs. To do so, CLCA describes how physical flows may change due to an increase or decrease in demand for the product system under study.

Unlike attributional LCA, which does not distinguish between restricted activities/suppliers, the system boundary of CLCA only considers activities/suppliers that can react to a (marginal) change in demand. Restricted suppliers are excluded. CLCA includes unit processes within and outside the immediate product system boundary and uses economic data to measure physical flows from indirectly affected processes. Allocation is avoided by expanding the system boundary [3].

Both attributional and consequential LCA are useful but serve to different purposes. The difference lies in how the boundaries are set, which will only result from a clear and unambiguous definition in the objective and scope phase of the study [4]. Attributional LCI aims at answering "How are environmentally relevant things (pollutants, resources, and exchanges among processes) flowing within the chosen temporal window?" Consequential LCI aims to answer "How will flows *change* in response to decisions?"

Hence, to understand the potential consequences of a decision under evaluation, the CLCA’s scope predicts what changes are induced and *the differences* between alternative product systems are modelled; all the rest remains constant (‘Ceteris Paribus’ principle) and is not modelled. Prox and Curran [5] explain the five-step procedure originally proposed by Weidema [6]: (1) describing the product by its properties; (2) identifying market boundaries; (3) identifying product alternatives; (4) defining the functional unit; and (5) determining reference flows for alternatives.

The functional unit is defined to provide a reference for related inputs and outputs, and it is a quantified description of the performance requirements that the product system meets [7]. The system boundary definition determines which processes should be included in the assessment. A ‘determining product’ is defined as a product for which demand is directly linked to its production. In contrast, increased/decreased demand for ‘dependent products’ – like most coproducts - has no influence on their production. As CLCAs are interested in responses to changes, such *restricted markets* are typically not modelled.

This paper aims to estimate the potential environmental consequences brought about by the implementation of the two main strategies envisioned in Roadmap BR:

reduction of the clinker factor and corresponding change in cement composition (alternative 1) and change in the fuel mix (alternative 2) used in production. Our baseline is the production system in 2014, modified by incorporating fuel mix and cement composition projected by the Roadmap BR for 2050. The computable general equilibrium (CGE) model was improved and further disaggregated relatively to a previous exploratory study [8], to improve the economic insights provided.

METHOD

To accomplish our goal, a two-stage approach was conducted. First, CLCA was performed using only the data published in Roadmap BR. Next, a computational general equilibrium (CGE) model of the Brazilian economy estimated the influence of the investigated technological changes within the cement production on other economic sectors.

CLCA MODELLING

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 Roadmap BR [1]: change in cement composition (route 1) and change in the fuel mix used (technology route 2) relative to cement production as per 2014 (baseline).

The time scope of the evaluation is 2014-2050. Therefore, the time horizon refers to short-term marginal effects ('operating 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. 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. Table 1 summarizes the characteristics of clinker and cement production as 2014 (baseline) and after the technological changes projected for 2050.

The functional unit (FU) used in this study is 1 t of cement in the composition projected for 2050 in Roadmap BR. Following the simplification that dependent products do not respond to increased demand and are typically not modelled in CLCA, the reference flows for the alternatives were determined, and the boundaries of the modelling system were defined (Figure 1).

The product system considered only the unrestricted products of the fuel mix (charcoal) and the clinker substitution palette (limestone and clay). In view of CLCA methodology, charcoal was the only thermal energy source analysed: its suppression from the fuel mix (0.21 GJ/t cement) represented most of the total displaced thermal energy (0.28 GJ/t cement).

Gbfs and fly ash were not included in the system boundary at this early stage because, like the residues in the fuel mix, they are considered as restricted markets. Finally, to account for the emissions used in the general equilibrium model, the

Brazilian economy's raw emissions data for 2014 from the National Emissions Registry System (SIRENE) were used.

Table 1: Characteristics of cement production as per 2014 (baseline) and after technology changes projected for 2050 [1]. Determining and dependent products as indicated.

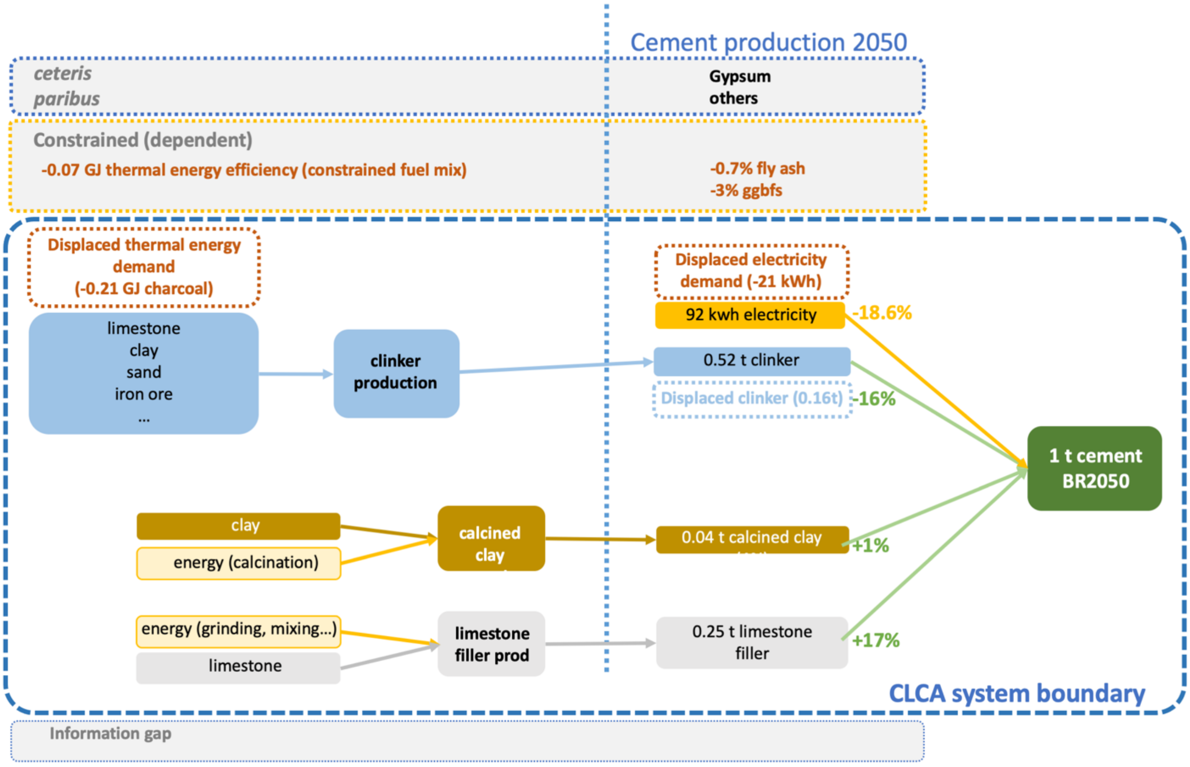
Inputs for producing 1 t of (average) Brazilian cement	
2014 (baseline) inputs	2050 Inputs
3.5% gypsum	3.5% gypsum
1% other	2% other (+1%)
14% ggbfs (dependent)	11% ggbfs (-3%) (dependent)
3% fly ash (dependent)	2.3% fly ash (-0.7%) (dependent)
3% calcined clay (determining)	4% calcined clay (+1%) (determining)
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% pet coke (dependent)	45% pet coke (-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 (-18,6%)

Source: the authors.

Table 2 shows material and energy flows resulting from the proposed technology changes relative to the reference unit – 1 t of cement (modified technology). The life cycle inventory is composed of secondary data from the Ecoinvent v3.4 database adapted to the Brazilian energy mix (background) and primary data for clinker production (foreground) and calcined clay collected by the research group in which this work is inserted.

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 Roadmap BR [1], as indicated in the CLCA system boundary (Figure 1). The datasets used were minimally modified for improved adherence to the Brazilian reality. Hence, electricity and water inputs were altered to national data. Clinker and calcined clay production datasets were formulated using Brazilian average information, incorporated into novel datasets later published in Ecoinvent version 3.6.

Figure 1: CLCA system boundary used in this study showing displaced energy (thermal and electricity) and materials (clinker) and added inputs (calcined clay and limestone filler). All dependent products (constrained markets) are excluded. Latin expression 'Ceteris Paribus' means "all the rest constant".



Source: the authors.

Table 2: Material and energy flows considered for producing 1 t of cement in 2050. The dataset for clinker was modified based on the primary data collected; the dataset for calcined clay was developed based on the primary data. The remaining (secondary) datasets were modified to account for the Brazilian context.

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

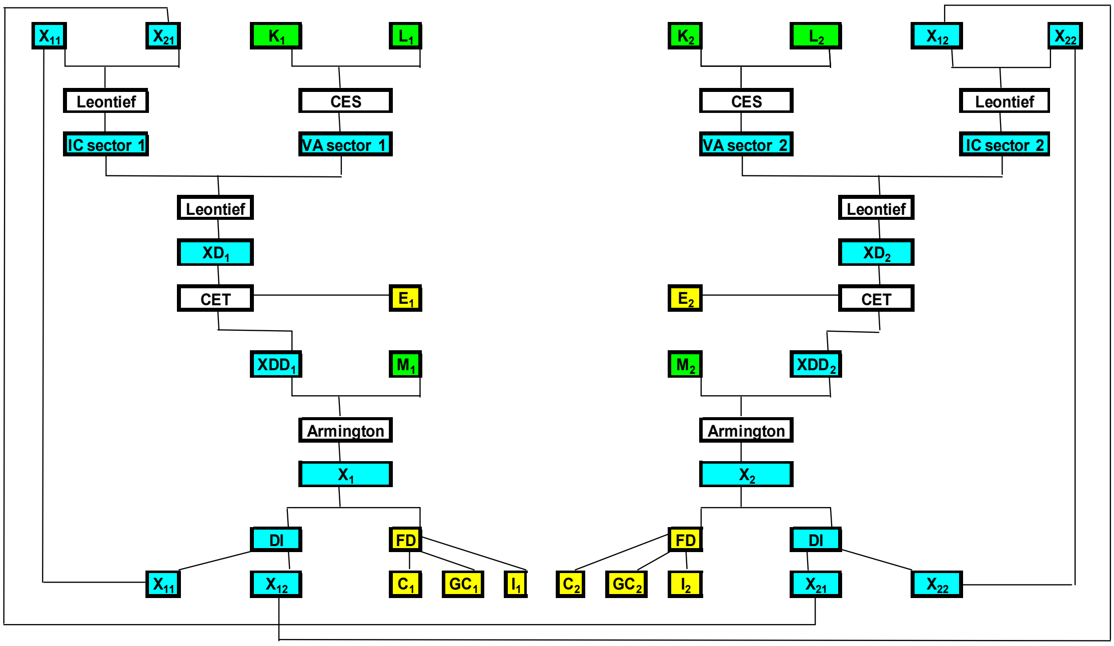
* Charcoal mass estimated considering a calorific value of 23 MJ/kg.

Source: the authors.

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. Figure 2 represents a simplified structure (considering an economy with only two sectors) of the CGE model used in this paper, originally presented by [8].

Figure 2: Simplified structure of the CGE model used in this study.



Source: the authors.

The production level of each sector (j) of the domestic economy (XDj) will combine an aggregate of the intermediate consumption (X11 e X21 for sector 1) with value added (VA) through a Leontief function (a function that uses inputs in constant proportions). In turn, the value added in each sector uses the capital (Kj) and labor (Lj) factors through a CES (Constant Elasticity of Substitution) function, which allows the substitution between these two factors when their relative prices change. On the other hand, the intermediate consumption from a sector (XDj) refers to the use of inputs in a constant proportion (Leontief Function), and each of these inputs is in turn a combination of domestic and imported inputs.

Each sector of the domestic economy produces a single product (XDj), that some part stays in the domestic market (XDDj) and other part is exported (Ej); the decision on the quantity that stays in the domestic market and that which is exported is defined by a CET (Constant Elasticity of Transformation) function, which considers changes in the relative prices of this product in the international and domestic markets.

The domestic production of a given product (XDDj) is combined with the importation of this product (Mj) through an Armington function (which considers the relative prices of that product in the domestic and international markets) that results in the supply of this product (Xj) in the domestic economy. In turn, each sector supply (Xj) will provide products to furnish household consumption (HC), government consumption (GC), investments (I) (essentially civil construction and capital goods) and intermediate consumption (IC).

This CGE model is built upon some classical assumptions: (i) the supply of each good and each factor of production (capital and labour) 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 labour in each sector of the domestic economy derive from the CES function that combines these two factors to result in value added; the demand function of household consumption by each product 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), and finally the supply of public services also results from a Cobb–Douglas function (in this case, spending on each service is constant relative to government’s collection).

Exogenous changes regarding altered input for cement production projected for 2050 were applied to the CGE model equilibrium describing the Brazilian economy in 2014 (Roadmap BR’s baseline year). In addition to quantifying the increase in the activity of each sector, it was verified if such increase caused any rebound effect, i.e.: if the decrease in GHG emissions in the cement industry increased those of other sectors.

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

RESULTS AND DISCUSSION

Table 3 shows the environmental impacts of CLCA disregarding the restricted markets and the effects of the proposals of Roadmap BR for improving the cement industry on other sectors of the Brazilian economy. Figure 3 breaks them down into main contributors.

Clinker substitution reduces a large part of the environmental burden in most impact categories. This is due to the materials involved in its composition and the energy required in processes such as calcining, grinding and blending.

Electricity also contributes significantly to the reduction of some impact categories, as the modified manufacturing process is more energy efficient due to the combined decrease in electricity demand (from 113 to 92 kWh/t cement) and thermal requirements.

Table 3: CLCA results for altered energy and material flows relative to the 2014 baseline.

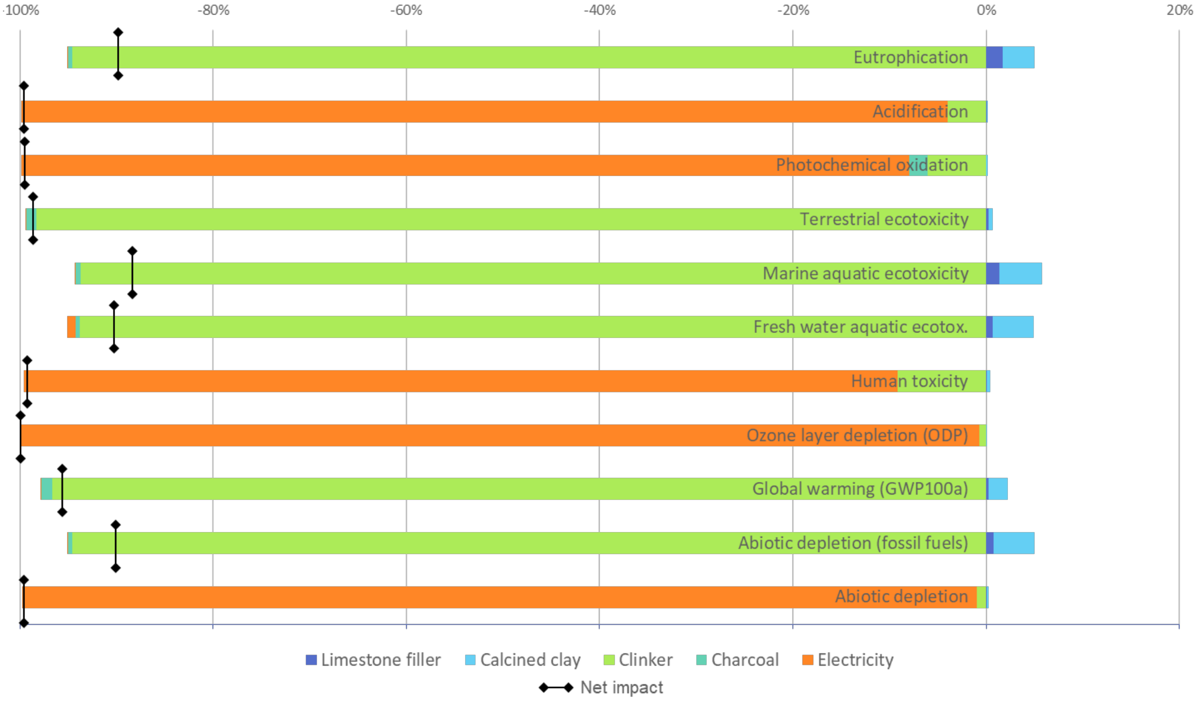
Impact categories	Unit	Added impact		Impact reduced		
		Limestone Filer	Calcined Clay	Clinker	Charcoal	Electricity
Abiotic Depletion	kg Sb_{eq}	1.591E-06	4.489E-06	-2.438E-05	-3.353E-07	-2.459E-03
Abiotic Depletion (fossil fuels)	MJ	5.971E+00	3.237E+01	-7.294E+02	-3.391E+00	-8.641E-03
Global warming (GWP100a)	kg CO_{2eq}	4.640E-01	3.286E+00	-1.641E+02	-1.903E+00	-1.691E-04
Depletion of the oxonium layer	kg CFC-11_{eq}	6.701E-08	1.772E-07	-3.941E-06	-3.848E-08	-5.314E-04
Human toxicity	kg 1,4-DB_{eq}	2.148E-01	2.621E+00	-5.823E+01	-1.045E-01	-5.758E+02
Fresh water ecotoxicity	kg 1,4-DB_{eq}	1.032E-01	6.684E-01	-1.476E+01	-7.157E-02	-1.379E-01
Marine ecotoxicity	kg 1,4-DB_{eq}	4.309E+02	1.469E+03	-3.069E+04	-1.586E+02	-2.870E-01
Terrestrial ecotoxicity	kg 1,4-DB_{eq}	3.976E-04	7.766E-04	-1.704E-01	-1.839E-03	-8.956E-08
Photochemical oxidation	kg C_2H_{4eq}	1.266E-04	1.059E-03	-4.077E-02	-1.279E-02	-6.201E-01
Acidification	kg SO_{2eq}	6.465E-03	6.481E-03	-3.299E-01	-1.313E-03	-7.980E+00
Eutrophication	kg PO_{4---eq}	1.840E-03	3.677E-03	-1.041E-01	-4.408E-04	-2.126E-06

Source: the authors.

After the exogenous changes regarding clay, limestone and charcoal input were applied, the new economic equilibrium captured by the CGE model for 2050 showed that the industry-proposed changes would (a) increase its economic efficiency, reducing the cement's manufacturing cost, hence the product's price, and ultimately increasing product's demand and production; and (b) affect prices, hence, production levels of all 35 sectors of the economy.

The economic model assumes that the inputs are used in constant proportions. Therefore, the additional demand for cement propagates production increases on 20 economic sectors, while the remaining 15 sectors would present some reduction in the level of activity. For simplicity, the list in Table 4 is truncated to show only the sectors with the highest increments or reductions in production level. Obviously, the cement sector shows the largest increase in production, because it is directly affected by its cost reduction. But it also directly stimulates, for example, the construction sector, in addition to the general increase in all economic activity.

Figure 3: CLCA results for altered energy and material flows relative to the 2014 baseline (vertical line at 0%). Bars at the negative (left) side of the horizontal axis indicate impacts reduced.



Source: the authors.

Table 4: Sectors with the largest production level increments (top 5 lines) or reductions (bottom 5 lines) after applying the cement technology change.

Sector	Change in production level	ΔGHG emissions (Gg CO_{2eq})	2014 GHG emissions (Gg CO_{2eq})
Cement	0.5102%	0.21	41
Water, sewage and waste management	0.2230%	0.02	7
Manufacturing of non-metallic mineral products	0.2224%	0.37	167
Construction	0.1036%	0.00	0
Extraction of nonferrous metallic minerals, including beneficiation	0.0295%	0.11	373
Extraction of oil and gas, including support activities	-0.1241%	-8.41	6,776
Oil refining and coking plants	-0.1598%	-768.03	480,618
Forestry production; fishing and aquaculture	-0.2689%	-113.77	42,309
Limestone extraction	-8.8365%	-9.29	105
Clay extraction	-17.9747%	-3.37	19

Source: the authors.

Most importantly, our findings showed that, in the 35-sector economy balance: (a) the reduction of emissions in the cement sector did not push emissions to other sectors, and (b) an overall decrease of 941 Gg CO_{2eq} in 2050, relative to 2014, would be expected, mostly related to three sectors: forestry production, fishing and aquaculture (113.77 Gg CO_{2eq}); oil refining (768.03 Gg CO_{2eq}); electricity, gas and other utilities (75.86 Gg CO_{2eq}).

CONCLUSIONS AND FINAL REMARKS

The Roadmap BR [1] pointed out an opportunity for reducing carbon intensity by one third whilst increasing cement production in 2050, by implementing alternative technological routes. The CLCA showed that the two technological routes considered for impact minimization generate positive effects: whilst the sector's carbon intensity is significantly reduced, all other impact categories evaluated showed net reductions of at least 80%.

The CLCA also showed a 0.5% increase in the level of activity of the cement sector. Increases and reductions in the level of activity in the other sectors of the economy were also estimated, but calculating the corresponding emissions were outside the scope of this work. Nonetheless, the corresponding increase in the cement industry emissions (0.21 Gg CO_{2eq}) do not cancel out the significant benefit assumed from the expectations indicated in Roadmap BR - a decrease of 941 Gg CO_{2eq} in the total economy balance - which excludes the possibility of a rebound effect on other economic sectors.

This study was sometimes hindered by the absence of representative national inventory data. We attempted to limit this issue through dataset adaptation to best represent the national production scenario.

No prospective scenarios regarding alterations on the Brazilian electricity grid until 2050 were considered in the predictions herein presented. This aspect could be further investigated as future work, to see if this assumption had a relevant impact on the results.

Consequential LCAs are usually coupled with the stepwise 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 concepts without increasing data collection complexity. Such ease of application may bias perception of the economic sector's response though.

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.

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