



Limestone calcined clay cement as a low-carbon solution to meet expanding cement demand in emerging economies



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ABSTRACT

This paper aims at assessing the return on investment and carbon mitigation potentials of five investment alternatives for the Cuban cement industry in a long-term horizon appraisal (15 years). Anticipated growing demand for cement, constrained supply and an urgent need for optimisation of limited capital while preserving the environment, are background facts leading to the present study. This research explores the beneficial contribution of a new available technology, LC³ cement, resulting from the combination of clinker, calcined clay and limestone, with a capacity of replacing up to 50% of clinker in cement. Global Warming Potential (GWP) is calculated with Life Cycle Assessment method and the economic investment's payback is assessed through Return on Capital Employed (ROCE) approach. Main outcomes show that projected demand could be satisfied either by adding new cement plants—at a high environmental impact and unprofitable performance— or by introducing LC³ strategy. The latter choice allows boosting both the return on investment and the production capacity while reducing greenhouse gas (GHG) emissions up to 20–23% compared to business-as-usual practice. Overall profitability for the industry is estimated to overcome BAU scenario by 8–10% points by 2025, if LC³ were adopted. Increasing the production of conventional blended cements instead brings only marginal economic benefits without supporting the needed increase in production capacity. The conducted study also shows that, in spite of the extra capital cost required for the calcination of kaolinite clay, LC³ drops production costs in the range of 15–25% compared to conventional solutions.

1. Introduction

Concrete production has an impact on the climate as it accounts for 5–8% of total anthropogenic CO₂ emissions [1]. 95% of this CO₂ is produced during the fabrication of cement, half of it being released by the decarbonation of the limestone during cement fabrication. Cement is, after power generation, the second largest source of anthropogenic CO₂ emissions [2], and also the second most consumed product, after water. Furthermore, the rapid urban development in emerging countries will push forward the cement demand and recent studies estimate that cement production could represent 10–15% of global CO₂ emissions by 2020 [3].

There is indeed a strong link between economic growth, population and cement demand [3,4]. For low income levels (< US\$ 8 000, at

1990 levels), cement demand is proportional to the Gross Domestic Product, GDP. This is consistent with the fact that economic growth begins with a quick build-up of industrial and transport infrastructure, and concrete is by far the most used material for this purpose. In industrialized countries with higher income levels, cement demand and population evolve proportionally. They have developed their infrastructure decades ago, and thus, demand for cement is limited to maintenance and marginal improvement of infrastructure to cope with population growth [3].

Cement production in 2014 was 4.3 billion tonnes. Emerging economies (China, India, CIS, others Asia) account for roughly 3.5 billion tonnes, 81% of the world's production. Industrialized countries (Europe, USA, Japan) produced roughly 0.4 billion tonnes, 9% of the world's cement production [5]. According to the Eleventh Edition of

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the Global Cement Report, global cement consumption was still on the rise in 2015 and further increase for 2016 is expected, notwithstanding that there will be a slower rate than in the past [6].

Most cement consumption takes place in the fastest-growing economies like China, India, Russia, South Africa, Brazil, Mexico and Chile. From an investment perspective, the stock markets of these countries are more volatile than the mature markets of developed countries but offer higher returns. This makes them more attractive as well as riskier. Concerning Cuba, the opening-up process currently undergoing and the untied relationship with US government, will most probably boost the overall investment, thus, fostering the development of new infrastructure [7,8]. The regulatory framework in the country portrays a secure and less risky place where to invest with promising higher profitability and faster payback periods. This also might be the case of many other emerging economy's countries. "Now that Cuba has relations with the United States, the country risk has diminished for foreign investors" [9].

The growth in cement demand in most dynamic economies takes place within short periods. Annual growth rates between 5–15% are common in these scenarios. Coping with a sudden demand could be an issue for the cement industry because installing production capacity is a capital intensive and time consuming process (setting up a new cement plant, 1.0 M tonnes per year would cost more than 250 Million US dollars, and would take around 4–5 years to be operational) [10,11]. Commonly, the period of building up infrastructure in emerging economies ranges between 20 and 30 years. After 20 years, demand enters a stabilization phase that lasts 10–15 years (plateau), and as soon as infrastructure is in place, demand declines. Meeting peak demand prompts for a detailed investment strategy, due to the risk of installed capacity exceeding demand within the payback period.

Cuban cement consumption has historically been following the same trend of production output, since demand exceeds the supply by far. There is a large accrued backlog in demand in the country due to some structural and case-specific reasons. Forecasted demand based on the cement group's estimations would be in the order of 18%, 15% and 10% growth rate by the subperiods 2016–2020, 2020–2025, 2026–2030, respectively. The ongoing opening-up process and economic reform in Cuba could possibly foster new joint ventures with a steady potential in the cement industry.

Facing the upward-sloping demand for traditional cement with a very high clinker to cement ratio is no longer bearable for Cuba or for faster-growing economies. Therefore, required cement turnover in cement companies is claimed to be in accordance to global concerns, which means targeting economic goals without impeding the climate change mitigation goals. Bearing this in mind, a shift from conventional to alternative technologies becomes an imperative.

The use of Supplementary Cementitious Materials (SCM) has been well-grounded and well-documented [12–17]. Different clinker substitution levels can be achieved depending on the type of SCM and its particular pozzolanic reactivity. However, limited world wide availability and limits in clinker replacement hinder the ultimate benefits of these substitutions. Other alternatives such as geopolymers have been developed [18,19]. They can have interest in terms of carbon reduction and resource consumption but their use is foreseen in a medium to long term perspective. Among these alternatives, Limestone calcined clay cement, coined as LC³ has been developed. A deeper understanding on the technical development of LC³ can be found in [15,17,20].

This paper focuses on the assessment of the different options in terms of cement technology for the Cuban cement industry, through their economic benefits and carbon mitigation potentials. The financial success was measured using the Return on Capital Employed (ROCE) approach. The environmental impact is considered with Global Warming Potential through CO₂-eq., which enables addressing carbon savings among technological scenarios.

2. Description of alternative technologies for cement production in Cuba

2.1. Cuban cement industry: overview and prospect

Cuba was the pioneer in cement manufacture in Latin America. The first Cuban cement factory was set in production in 1895 with a productive capacity of 6 Ktpy [21]. Nowadays, the Cuban cement industry owns six factories, which all begin operations in the 1980's with a current nominal production capacity of 4.4 Mt per year. Historical cement production capacities increased vertiginously after the Triumph of the Revolution in 1959 as part of the industrialisation process carried out until the 1980's. An economic recession started in the late 1980's followed up by the crisis during the 90's. This was the hardest period for Cuban economy—without supplies or spares, capital for investment or maintenance— and its effect over industry is still visible. All capital investments in cement sector stopped and productive capacities started decreasing.

The cement sector in Cuba has now an installed capacity of 2.8Mt of clinker per year but only 43% of productive capacity can be used. In term of cement type, a variety of types of cement with a large predominance of Ordinary Portland Cement (OPC) and a smaller contribution of Pozzolanic Portland Cement (PPC) made with 20% zeolite addition. In term of clinker technology, 75% of the total clinker production is done with a dry process in two major cement plant (Cienfuegos and Curazao) (Fig. 1).

The best choice to meet demand spikes in the short term is to increase clinker substitution by using Supplementary Cementitious Materials (SCM). This enables the increase of cement production capacity without the need to increase clinker manufacturing capacity [23]. The main sources of SCM are waste from industrial processes, among others, granulated blast furnace slag, pulverized fly ash, natural pozzolans (including agriculture ashes and silica fume), artificial pozzolans and limestone. The use of SCM has proven to impact on the cost of cement, due to the substitution of clinker in cement production [24].

However, the use of SCM has some limitations:

- Clinker substitution is limited to 35% in most cement international standards, with the exception of slags, where up to 65% of clinker can be substituted. The average clinker substitution worldwide is around 25% [25].
- The availability of SCM, especially those of industrial origin such as fly ash and slag, is limited to certain regions. The main reserves do not occur in many places where cement demand will grow exponentially in the coming years. Current availability of SCM is approximately 10% of world's cement production [26].

The use of calcined clays has been limited to pure kaolinite clays to

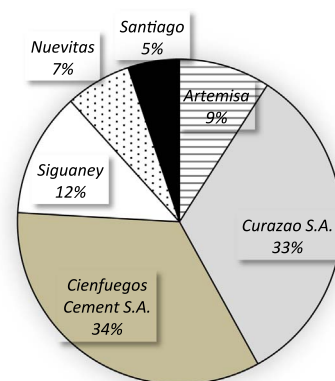


Fig. 1. Market share by factory in 2015. Data from [22].

produce metakaolin, (MK), a very reactive pozzolan resulting from the activation of the mineral kaolinite present in the clays. MK is however a very expensive material, whose use as SCM is often limited to 10% of cement substitution [27].

Recent developments have proven that a reasonably reactive material can be produced if less pure kaolinite clays are thermally activated to produce pozzolans [13,28,29]. Large deposits of suitable clays of kaolinite type are abundant in the tropical belt of the world, where economic growth is high, thus matching very well with the capacities for cement production. The inclusion of low grade calcined clays as pozzolan would dramatically increase the amount of SCM available at the global scale, and thus would enable further reduction of CO₂ emissions through substitution of clinker in blended cement.

2.2. Limestone calcined clay cement LC³

A new ternary blended cement has been developed based on the combination of Portland cement with calcined clay and limestone. The new cement can be produced with low quality-overburden material that is normally considered waste for traditional production: low-grade clay and dolomite rich limestone. Firing takes place at half the clinkerization temperature. Limestone is not calcined, thus it does not contribute to an increase in CO₂ emissions.

The calcium carbonate supplied through limestone to the system and the extra alumina provided by calcined clay will further react to form alumina phases [20]. In normal blended cements, the limit on pozzolan addition is 35%. The extra limestone provided in the system can further offset clinker while keeping the amount of pozzolan used at 35%. If the ratio calcined clay/limestone is kept at 2:1, this could provide further substitution of 15% of the clinker, for a total substitution of 50% of the clinker.

Despite the higher clinker substitution rate, the ternary system has a better performance compared to most binary systems with several types of pozzolan. Noticeably early strength of this system is much better than binary systems, because the alumina phase reacts vigorously during the first 7 days, thus overcoming the main problem of pozzolanic cements, which is the slow strength gain at early ages.

Technology for clay calcination demands temperatures around 700–850 °C [13,28,29]. To calcine clays, two technological options are discussed in this paper: stationary and flash calcination.

Stationary calcination takes place in rotary calciners very similar to clinker kilns. A suitable option could be an old wet process kiln refurbished to be a clay calciner [30]. The chains section could serve to dry and shred the original clayey material, thus avoiding the use of extra pre-processing facilities. The material has a residence time of around 60 min at the firing chamber, and the reactivity achieved is reasonably good [17].

Flash calcination takes place in special flash calciners. The original clayey material should be previously dried and ground to powder. It is then fed to a stream of hot gas at temperatures of around 800–900 °C, with residence time of a few seconds. The technology enables implementation of several heat recovery cycles, thus the potential for efficiency is high, with power consumption in the rate of 2211 MJ/t of metakaolin flash [31].

In terms of investment, refurbishing an old kiln is an interesting alternative for the industry, provided the capital costs are in the range of \$US 12/ton of cement, whereas the capital cost of a flash calciner is rated as \$US 24/ton of cement [31]. Either many cement plants have a redundant clinker capacity, which is normally an old, outdated clinker kiln, which is set into operation in times of a peak cement demand, or when there are gaps in production. This could be an alternative path for low-income level countries, which cannot afford the capital costs of expanding with new capital investments, but have an expanding cement demand to meet. This is especially critical for the cement industry, which is characterized by the low return on capital employed.

In environmental terms, there are some differences in CO₂ emis-

Table 1

Energy consumption and CO₂ emissions of various clay calcination technologies. Data from: [17,31].

	Technology	Energy (MJ)	Emissions (kg CO ₂)
Calcined clay	Kiln (Industrial Trial)	4234	393
	Refurbished kiln	3088	249
	Flash calciner	2734	196

sions between the two technologies at stake, basically linked with the energy efficiency of the technology. Table 1 presents the calculations of energy consumption during calcination as well as CO₂ emissions associated with clay calcination. Three alternatives are compared and assessed (i) the wet process clinker kiln temporarily adapted for the production of calcined clay for the industrial production of LC³ in Cuba, with energy estimated in ~4234 MJ/t calcined clay [17].

The increase of energy consumption for clay calcination at a refurbished clinker kiln is around 12% compared to the flash calcination, but CO₂ emissions rise to 21% only for clay calcination. If the analysis is done at the level of cement production, differences in energy consumption and CO₂ emissions between a flash calciner and a retrofitted clinker furnace are mitigated (a more detailed analysis of the attenuation Of emissions is discussed later in this article). Finally, it has to be noted that retrofitting of old cement plant is faster than building a new flash calciner. Only 6–8 months are required instead of 18.

3. Definition of investment scenarios

The Cuban cement industry reports production of 1.8Mt of cement in 2014 [32]. According to estimations from the cement enterprise group in the country [22], total cement production in 2015 equals 1.9Mt. The current demand exceeds production, which is a stimulus for investment in this sector to increase manufacturing capacity as well as its use efficiency. The outdated technology does not allow for a higher utilization rate due to the requirement for several periods of maintenance and repair of equipment and facilities. Actually, it can be considered that the utilisation rate of cement plant is close to 40% (Fig. 2).

Official government figures forecast cement demand of 3.5Mt/year by 2019 [22]. The demand projection at the anticipated peak demand phase (2016–2020) will grow 18% per year. This is linked to an expected boom in construction activity that normally occurs in emerging economies [33]. During the peak demand phase annual growth of 10% and 5% of demand are expected [3]. Expected Cuban cement demand is shown in Fig. 2.

For the Cuban cement industry to meet the sudden increase in cement demand, different scenario are considered. An overview of cement type proportion is shown in Fig. 3 and a detailed description of each of them is provided below.

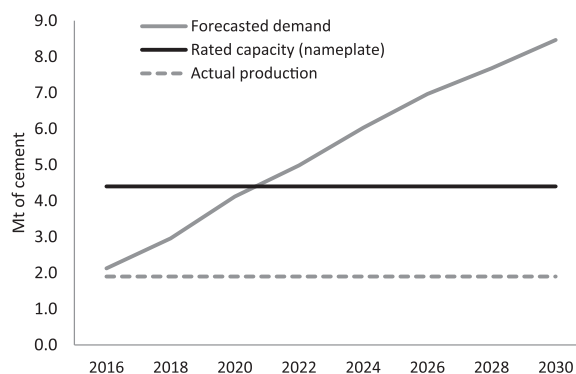


Fig. 2. Production capacity vs. growing demand over time. Data from: [22].

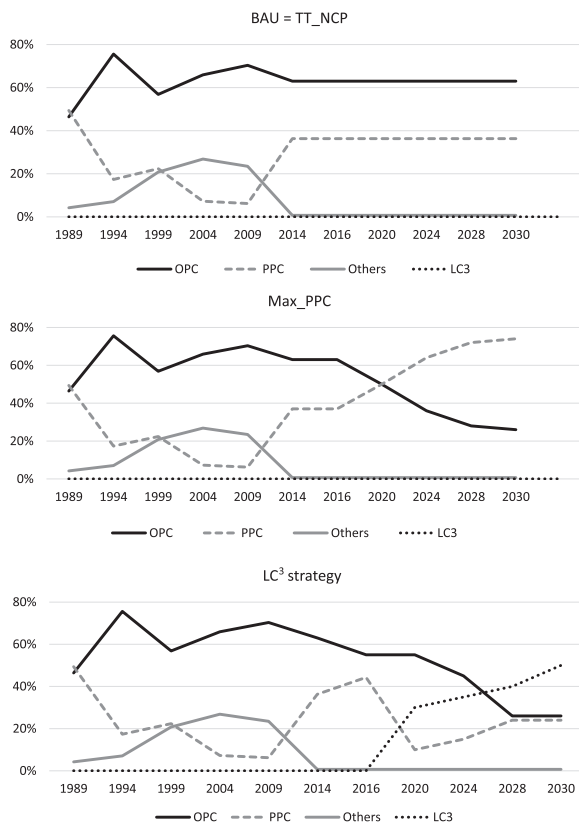


Fig. 3. (Up) BAU and TT_NCP (Middle) Max_PPC (Bottom) LC³_R and LC³_F.

Scenario 1: Business as Usual (BAU)

In this reference scenario traditional cement (OPC+PPC) proportions are maintained at the current level (63% vs. 37%). Investment are dedicated on maintaining and improve the existing infrastructure. Capital expenses will then be limited to:

- (1) finalize the ongoing process to set up Santiago Plant which will come in operation by 2019
- (2) upgrade one clinker kiln production line in Curazao Cement SA by 2021 (convert from wet to dry)
- (3) upgrade one clinker kiln production line in Nuevitas Plant by 2023 (convert from wet to dry)
- (4) regular repairs to maintain the outdated industry, especially those owned by the government.

Actions 1–3 will increase clinker capacity by 1.1 Mt each [22].

Scenario 2: Traditional cement technology plus new cement plants (TT_NCP)

In this scenario traditional cement (OPC+PPC) proportions are also maintained at the current level (63% vs. 37%), but higher investment capacities are foreseen allowing to build new cement plant when the demand increases. Investments in Santiago, Curazao S.A. and Nuevitas plants are then not considered in this scenario and new cement plants only provide the extra production capacity. According to the demand forecast, 6 new cement plants of 1 Mtpy capacity are required.

Scenario 3: Maximizing PPC (Max_PPC)

In this scenario, a change in cement type proportion is considered, but only with existing cement types. Furthermore, investment capacities are considered as reduced as the BAU scenario. Therefore, the

upgrade and maintenance of the existing cement plant is similar as BAU but cement proportion will move from 63% OPC–37% PPC to 25% OPC–75% PPC. The maximum PPC proportion has been calculated considering that a minimum amount of OPC was required for specific infrastructure work. Experiences of other countries with a more mature market such as India, where 25% of total cement production is OPC or France where the share of OPC in 2014 was also close to 25% support this choice.

Scenario 4: Retrofit old clinker kilns to convert into clay calciners plus LC³ introduction (LC³_R)

This scenario proposes the strategy of introducing LC³ into the Cuban cement industry. A gradual introduction is foreseen in order to reach 50% of the cement production with LC³ by 2050. In this scenario, low capital investment strategies are also considered and clay calciner are installed through the refurbishment of existing wet clinker kilns. Four calciners with 300 kt/yr of calcined clay are needed to satisfy the maximum LC³ production by 2030 (equal to 4.25 Mt, 50% of total cement production by that date). The investment in clinker kilns are similar as the one of the BAU scenario.

Scenario 5: Flash calciner plus deployment of LC³ (LC³_F)

This scenario is similar than the previous one but a higher investment capacity is considered allowing to implement flash clay calciner for LC³ production. The investment in clinker kilns are still similar as the one of the BAU scenario.

Hereinafter abbreviations in parenthesis–employed while defining scenarios will serve as reference letters for interpretation purposes.

Fig. 3 presents the historical series of cement production in Cuba and the forecast 2016–2030 according to scenarios evaluated.

4. Method and data

The success criteria assessment for the different scenario will be based on three parameters: the cement production capacity, the CO₂ emissions and the ROCE. Actually, considering the construction industry, the cement production capacity represents the availability to fulfil the demand and provides in that sense fundamental services such as infrastructure and housings to the population. Since LC³'s primary environmental benefit is based on GHG potential avoidance, this research explores CO₂-eq savings because of the implementation of the previously defined scenarios. This also helps to define the scope of the analysis pursued from the LCA perspective. Finally, the Return on capital employed shows the efficiency of the investment and therefore represents the most limited proxy to economic sustainability (profit) even if other economic criteria should probably be considered.

4.1. ROCE method: conceptual framework

Several studies have recently looked at the role of financial ratios in equity valuation [11,35–41]. The conceptual backbone of Return on Capital Employed (ROCE) can be traced back to 1920's, when the Du Pont Corporation developed what is commonly known as Du Pont accounting and ROCE as a measure of business performance to enable it to compare the performance of its many different business units [42]. The notion that the value of a company is a function of its expected cash flows is deeply engrained in finance. Actually, to generate these cash flows, though, firms have to raise and invest capital in assets and there is a cost to this capital. In fact, it is only to the extent that the cash flows exceed the costs of raising capital from both debt and equity that they create value for the company [43]. ROCE is then a reasonable financial measure that allows policymakers and investors make assessments on the ability of their assets to yield profits over time [44].

ROCE is usually calculated by multiplying *profit margin* (PM) with

capital turnover (CT) (Eq. (1)). Profit margin is a percentage of sales revenues, i.e. what share of revenue is kept in earnings. Capital turnover expresses how efficiently the funds have been used by the enterprise (or the industry) to generate incomes (efficiency or activity ratio). This can then be also expressed as the Eq. (2).

$$ROCE = \text{Profit Margin} \times \text{Capital Turnover} \quad (1)$$

$$ROCE = \frac{\text{Net Profit}}{\text{Sales}} \times \frac{\text{Sales}}{\text{Capital Employed}} \quad (2)$$

The Eq. (2) can be simplified and ROCE can then be expressed as earnings before interest and tax (EBIT) over capital employed [35,45,46].

In the current study, and due to the lack of fully consolidated data in the Cuban context, we have simplified the EBIT as amount earned by selling cement (quantity in ton multiplied by the cement price per ton) minus the Operational Cost of cement production (OPEX) calculated in a previous paper [47]. The capital employed is calculated as the CAPEX. Further detail on its calculation are given later.

In order to assess the effectiveness of a ROCE, it should be compared against Weighted Average Cost of Capital (WACC). The cost of capital [45,48–50] is the minimum required rate of return needed to justify the use of capital. For a deeper understanding of WACC's economic technicalities, thorough background can be found in [35,45,49,51].

Comparing ROCE against WACC is a reliable financial method to draw up conclusions on (1) the financial performance of a company, (2) the optimal capital structure of this company and (3) the feasibility of investment alternatives. The higher the ROCE, the better. If $ROCE > WACC$, the economic system being evaluated creates value for the money invested (or potentially invested). On the contrary, if $ROCE < WACC$, it is a clear pattern of unprofitability.

Finally, both cash in and cash out need to be adjusted for inflation, as the real value for money changes over time while prices are evolving. In this study, GDP implicit price deflator has been considered as a proxy measure for price escalation appraisal. The GDP price deflator is an economic metric that accounts for inflation by converting output measured at current prices into constant-dollar GDP (nominal GDP/real GDP*100). The GDP deflator shows how much a change in the base year's GDP relies upon changes in the price level. According to Cuban Statistical Yearbook [32], taking into consideration the last six years, the average inflation amounts 4.14% per annum. Assuming price escalation roughly hovering on this figure over the time horizon covered in this study, inflows and outflows for ROCE calculations are adjusted so that they reflect the purchasing power of money over time.

Despite the robustness of this approach, it has not been used to assess economic potential of alternative cements. It has still been recently applied to European cement industry [11,36] demonstrating the robustness of this tool to assess the profitability of a capital intensive industry over a business cycle. Various scenario were considered but no high substitution clinker scenario.

4.2. Data collection

This section provides clarification on data obtained for further usage in economic and environmental assessment of possible alternatives.

4.2.1. Operational economic data (OPEX and cement price)

Table 2 presents the production cost of cement types as well as their current prices. Unit production costs are taken from the previous work of [17,47], who have studied the economic feasibility of LC³ against traditional cements in Cuban cement industry.

Note that in order to guarantee consistent assumptions towards comparability among alternatives, the potential price of LC³ has been fixed in line with the current price of its nearest surrogate binder, i.e.

Table 2

Unit price and operational cost. Data from: [47].

Cement type	Production cost (USD/t)	Price (USD/t)
OPC	72.02	116.05
PPC	66.67	108.33
LC ³ _R	61.42	108.33
LC ³ _F	56.41	108.33

Portland Pozzolan Cement (PPC), which also belongs to the blended cements family. Hence, a marginal increase in profit margin would directly come from the LC³ cost-effectiveness as compared to traditional high clinker content cements.

4.2.2. Capital expenditures (CAPEX)

Capital cost data have been sourced from Cuban cement industry report on long-term planned investment, for scenarios involving the upgrading and maintenance of existing infrastructure. Other investment costs on new technology or transformation of old cement plant into clay calciner are coming from literature [10,25,31,52–55].

According to technology paper number 25 (joint report by Cement Sustainability Initiative and European Cement Research Academy), the CAPEX for retrofitting a kiln is equal to 12 MEUR (~14MUSD, using an exchange rate of 1.2 USD/EUR). Taking into consideration that outdated kilns will potentially be refurbished, a lifetime of 15 years is presumed. In order to judiciously distribute capital expenditures throughout the service life of fixed capital assets, this paper employs straight-line method (linear depreciation) rather than double declining balance or sum-of-the-years' digit method.

The preferred recommendation is the linear depreciation method in order to guarantee homogeneously distribution of investment expenses over the service life of assets. Moreover, Act-Resolution 701/2015 of the Cuban Ministry of Finance supports the choice of depreciation method. Each clay calciner resulting from refurbishment could achieve 300 000 t of metakaolin per annum (0.30 Mt). Following the proportions described in Fig. 3, the investment timetable required for retrofitting clinker kilns is as follows: 1 in 2017, 1 in 2019, 1 in 2022 and 1 in 2024.

Based on ARGECO-Demeter Technologies, a French company that became pioneer in clay flash calcination to produce metakaolin in an economical and efficient way, a small plant for this purpose (the one they have been using since 2006 up to date) holds a CAPEX rising to 6.08 MEUR (~7.0 MUSD) [31]. Calculations on depreciation expenses are done over a 25-year lifetime. However, this is a very small plant. Its production capacity is 80 000 t per year (0.08 Mt). It is expected to reach 4.25 Mt of LC³ by 2028, which means requiring 1.28 Mt of metakaolin. It is technically feasible either with 4 retrofitted kilns or with 16 flash calciners of Demeter. In terms of unit CAPEX, recovering calciners as from kilns would cost 12 USD/ton of LC³ cement, while acquiring flash calciners totals 24 MUSD/ton of LC³.

Investment milestones have been strictly considered to obtain the grand total of CAPEX in each scenario in order to count the intertemporal gap while dealing with depreciation. The investment program for LC³_F is meant to be as follows: 4 in 2017, 4 in 2019, 4 in 2022 and 4 in 2024. It has to be noticed that for each retrofitted calciner, 4 flash calciners are needed in order to reach the same metakaolin, as the production capacity of one retrofitted calciner is four times larger than flash one.

According to [10], a new cement plant with 1Mt production capacity and a 25 year-lifetime totals 263 MEUR (315 MUSD). For the TT_NCP scenario, meeting the projected demand is fully anticipated. This CAPEX figure was employed in the form of the depreciation of expenses over time because extra capacity is needed to fulfil forecasted demand. A new cement plant would be required by 2017,

Table 3

Planned investments Cuban cement industry (BAU scenario), MUSD. Data from: [22].

Short-term					
Year	2016	2017	2018	2019	2020
Investment	70.00	90.00	140.00	56.00	54.00
Middle-term					
Year	2021	2022	2023	2024	2025
Investment	80.00	83.50	84.50	55.50	74.00
Long-term					
Year	2026	2027	2028	2029	2030
Investment	69.00	44.00	84.00	74.00	44.00

2019, 2021, 2023, 2025 and 2027.

Table 3 shows the foreseen investment amounts in Cuban cement industry, for the alternative Business As Usual.

In order to maintain the current clinker capacity with the outdated cement plants, in this paper it is assumed ~30MUSD/year as the minimum required investment, the cost that has been charged to the remaining scenarios. This assumption is derived from the Cement industry report cited above—in which investment is broken down and properly itemized—by summing up the items directly related to actions conducive to the increase in clinker capacity. This convention is applied to deriving capital employed in the rest of the alternatives under assessment, i.e. in scenarios from 3 to 5, investments encompass the extra CAPEX associated with clay calcination machinery (in LC³ options), as well as the cost of a new cement plant in the case of NCP option.

4.2.3. Environmental foreground data

The environmental assessment of one ton of cement as a functional unit using a life cycle assessment methodology (LCA) with a cradle-to-door approach was addressed by [17,47] in the Cuban cement industry. The studied production system was delineated for five main processes: (1) extraction and preparation of raw materials in the quarry, (2) extraction of fuel which includes the extraction and refinement of the fuels used throughout the process, (3). Transport of raw materials and fuels, (4) clinkerization and calcination of clays for LC³, and (5) grinding and packaging. This study does not include emissions of air pollutants or detailed quantification of NO_x, SO₂ and CO, which is a limitation and a gap to close in future research. Table 4 summarizes the unit CO₂ emissions for each cement type relying on the cement process type. These figures were further used as input data by each of the scenarios, according to the cement production structure taking into account the technological changes over time. The figures derived for wet process have been used for the environmental loads coming from the most outdated cement plants, which holds wet technology. However, 67% of total cement in Cuba is produced in Cienfuegos S.A and Curazao S.A. plants, both holding a dry process.

Each new cement plant within the industry is assumed to be of dry process, according to available cement technologies worldwide [10,24,30].

4.2.4. Derivation of a proxy WACC for Cuban cement industry

Cuba has a centralized-planned economy, dominated by state-run

Table 4CO₂ released per ton of cement and different process type: [17,47].

CO ₂ emissions (kg CO ₂ -eq/t)		
Cement type	wet	dry
OPC	1017	890
PPC	879	765
LC ³ _R		562
LC ³ _F		550

Table 5

Weighted Average Cost of Capital (WACC) for Latin America Emerging Economies (LAE).

Country	Company	WACC (%)
Brazil	Votorantim Cimentos/InterCement Brazil SA	11.5/8.7 [56,57]
Colombia	Argos/Cemex Colombia SA	12.6/10.3 [58,59]
Chile	Bio Bio	9.2 [60]
Peru	Cementos Pacasmayo/Unión Andina de Cementos SA	11/8.3 [61,62]
Mexico	Cemex	6.8 [63]
Mean (calculated based on mean values of WACC by country)		9.4

enterprises. Weighted Average Cost of Capital (WACC) is therefore difficult to estimate now although current investment are clearly showing the emergence of a free market. The foremost cement producers in Cuba are Cienfuegos Cement SA and Curazao Cement SA. The former is a joint venture in which Holcim holding accounts for 50%. The latter is a joint venture with 50% holding by Cemex S.A.B. de C.V. 67% of overall cement production in Cuba is then manufactured by mix-capital enterprises.

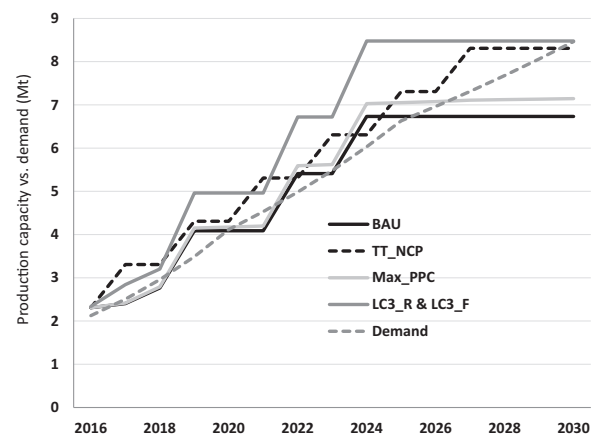
On these grounds, the WACC value considered in this study as a yardstick to evaluate the financial viability of the investment has been taken from the average of the WACC from the main Latin-American cement industry. Value are presented in Table 5. The mean value for WACC in Latin America cement companies is around 9.4%, ranging between minimum (6.8%) and maximum (12.6). A higher value as the average WACC is more reasonable for Cuba, leading to rather 12 than 9% of WACC as a safe horizon for cement development in the Caribbean island.

5. Results

5.1. Evolution of the relationship between cement production capacity and demand upon alternatives

Fig. 4 shows the calculated cement production capacity for the different scenario considered and compare them with the forecasted demand. In the BAU scenario, the demand would exceed the cement manufacturing capacity by 2025. Increasing the clinker substitution with the development of blended cement (Max PPC) allows to slightly increasing the production capacity but it is not sufficient.

Investing in new cement plant is of course possible and allow fulfilling the demand (TT_NCP scenario). Finally, in LC³ scenario, production capacity is also fulfilling the demand. Furthermore, the production surplus could be exported and represent an additional revenue for the cement industry.

**Fig. 4.** Projected demand versus production capacity.

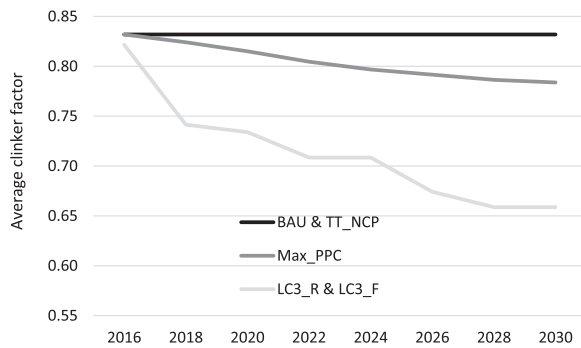


Fig. 5. Average clinker factor in scenarios foreseen.

5.2. Environmental implications (CO₂ mitigation)

The Fig. 5 shows the evolution of the clinker factor in the Cuban cement industry depending on the considered scenario. It is obvious that scenario where no change in cement composition are expected do not allow a reduction in clinker factor (BAU, TT_NCP). It can still be noticed that the LC³ option allows a higher reduction in the clinker factor than conventional blended cement (PPC) but that this reduction is also much faster.

The trend observed in the clinker factor evolution is constraining the evolution of the greenhouse gas emission per ton of cement. The contribution to climate change, expressed in CO₂ equivalent is shown in Fig. 6. It can be noted that on top of the average clinker factor of the cement production, the environmental impact is also linked with the efficiency of the clinker production. Consequently, scenario where only an improvement of the efficiency of the production infrastructure is done (TT_NCP and BAU) still allows a slight reduction in CO₂ emissions. The increase of blended cement (PPC) induces a higher reduction, while the LC³ implementation can achieve the highest and fastest improvement of the environmental impact. When flash clay calcination technology is implemented, environmental abatement will be bounded from 11% to 23%, which difference is negligible against kiln retrofitting strategy. These results are in accordance with those found in [47].

5.3. Economic caveats (ROCE)

The Fig. 7 shows the evolution of the ROCE over the year for the different considered scenario. The main results can be summarized as follow.

- Scenarios pursuing a low clinker content, namely LC³_R, LC³_F and Max_PPC, provide the best ROCE results. Max_PPC more than

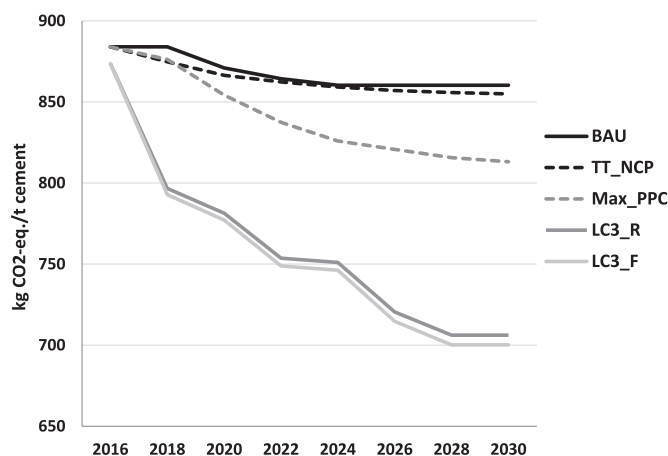


Fig. 6. Environmental impact of 1 t of cement under different scenarios.

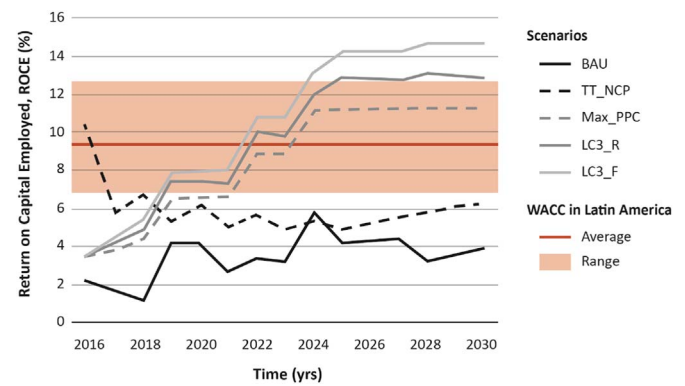


Fig. 7. ROCE for the scenarios evaluated.

double its ROCE compared to the BAU scenario during the last seven years. By the last 6 years under analysis, LC³ strategies retain ROCE gains in the order of around 2 (LC³_R) and 4 (LC³_F) percentage points with respect to the surrogate blended cement (Max_PPC). There is no major difference in terms of ROCE between LC³_R and LC³_F, even if the later has a slight advantage. Both LC³ scenarios follow the same trend in terms of profitability and return on investment along the business cycle.

- Investing in new cement plants in order to meet expected demand induces ROCE to stabilize at around 6% throughout the period, which is higher than the profitability of the BAU. It is however below any possible WACC in Cuba. This scenario is therefore not profitable in terms of investment strategy. These low ROCE value for traditional cement production is a known trend in other countries (See [11,36]).
- On the contrary, the LC³ scenario allow achieving ROCE value above the average WACC of Latina America cement industries by 2024. The flash calciner scenario seems to be the most promising with a ROCE of 14% over the last 6 year of the studied period.

5.4. Identification of the optimal solution

The optimal scenario compared to our target objective would be a scenario allowing the highest return on investment (ROCE > WACC), a production capacity that exceed the demand and the lowest environmental impact per ton of cement produced. Improvement from an environmental and economic perspective compared to the BAU scenario for the different alternative option are plotted in Fig. 8. The improvement is calculated by comparing the scenario in 2030. The upper-right position in the graph indicates the most eco-efficient route.

The strategy of introducing LC³ technology with the flash calcina-

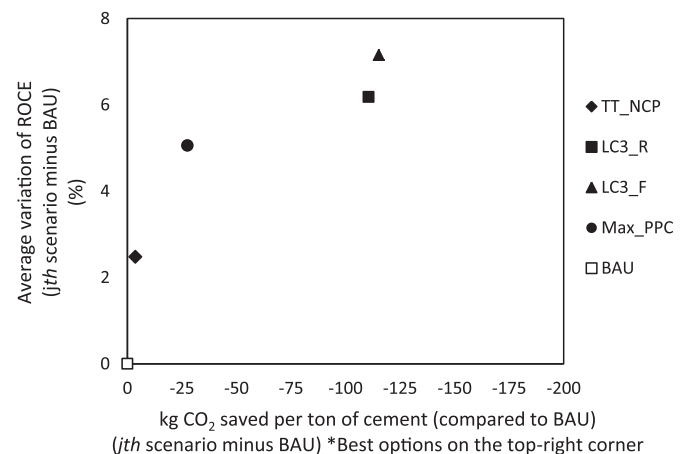


Fig. 8. Economic-ecological efficiency of options.

tion process is the optimal solution, since a slightly higher return on capital employed is achieved along with an almost negligible difference with respect to LC³_R in terms of CO₂ emission factor. This said, to produce LC³ by calcining the kaolinite clay in refurbished kilns, would be an alternative feasible solution with similar economic and environmental effects. Considering the speed of installation of the infrastructure (6 months vs 18 months) might be an additional advantage for the retrofitting option even with a lower ROCE. Actually, retrofitting old wet clinker kilns is a matter of domestic investment, with no CIF price playing its role. The acquisition of flash calciner and its shipment might take longer for the start-up of clay calcination facilities whilst the trend in the domestic market will provide an indication for potential demand in the short run.

The blended cement scenario (Max_PPC) seems to provide a clear economic advantage compared to BAU but without allowing a drastic reduction in CO₂ emissions.

6. Discussion

6.1. Sensitivity analysis

In the present study, we have been able to show that LC³ scenarios provide the highest return on investment. However, one can wonder how sensitive is this conclusion due to all hypothesis done. In this section, a sensitivity analysis is carried to evaluate the elasticity of the ROCE in relation to the input parameters: selling price, OPEX, CAPEX and demand.

Three trends can be inferred depending on the absolute value of elasticity: (1) elasticity greater than 1 that means the target variable is elastic (i.e., quite sensitive), (2) elasticity less than 1 (inelastic; not sensitive) and (3) unit elasticity, when it is equal to 1. Results for all scenarios are shown in Fig. 9.

Variation of demand and capital required for investment (CAPEX) have a direct influence on the ROCE and it is similar for all scenarios. An increase of the demand higher than expected has of course, a positive effect on ROCE while a higher CAPEX has a negative effect. One has to note that investment can be assessed with relatively high confidence now where they are planned, while demand expectation are much more uncertain. For the two other variables, the selling price and the operation costs, it is interesting to note that LC³ scenarios exhibit the lowest elasticity on ROCE. Finally, LC³ flash calciner scenario is the only scenario to have an elasticity lower than one for the production cost parameter. This aspect is very interesting as it shows the higher robustness of this scenario to possible energy price variations.

Given that energy is the primary driver of emissions in cement production, a sensitivity analysis has been conducted for carbon dioxide and ROCE emissions by varying the primary energy source used for clinkerization and calcination of the clay. The different fuels

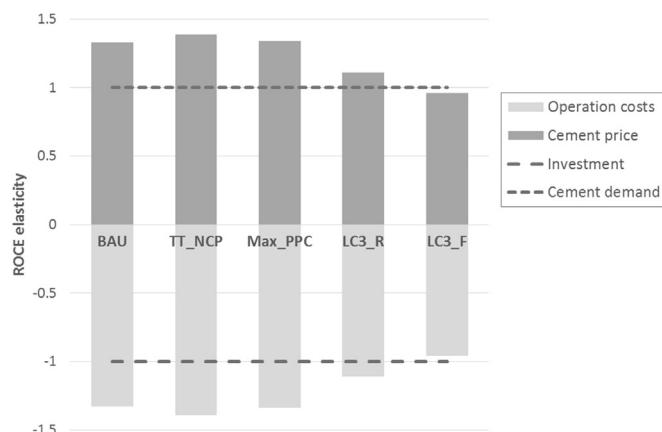


Fig. 9. Elasticity of ROCE given by the variation in input data.

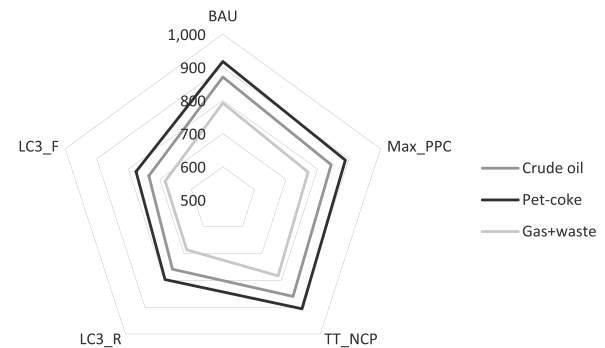


Fig. 10. Sensitivity of carbon dioxide emissions by type of fuel.

used in the analysis were: (1) crude oil, (2) petcoke and (3) waste + gas. The last element assumes a mixture of 70% waste and 30% gas. The CO₂ per ton of cement, expressed in kg, is the magnitude shown in Fig. 10. An average value over the next 15 years has been taken for schematic and simplification purposes. The radar diagram shows that the use of petcoke has a greater impact than crude oil and the combination of waste + gas. However, despite the use of petcoke (worst-case scenario for the Cuban context), the production of LC³ technology remains a competitive alternative in terms of environmental impact reduction. The combination of waste + gas allows for a greener production of cement. The use of this energy source combined with the production of LC³ technology would help position the Cuban cement industry as a low-carbon industry.

In economic terms, the ROCE was recalculated according to the fuel used, as described above. Fig. 11 shows the average ROCE value over a 15-year period. *Mix fuel* describes the current combination of energy for cement production in Cuba, which is the use of petcoke for clinkerization, crude oil for calcining clay.

Recently, the country's modern factories have been favored by the stable supply of petcoke following bilateral negotiations between Venezuela and Cuba. This is particularly important for reducing the average energy cost for the cement industry, even though CO₂ emissions are higher than for the other fuels studied. However, the preferential prices for petcoke in Cuba do not allow an objective comparison in this study. The international prices referenced by the International Energy Agency (IEA) and the US Energy Information Administration (EIA) will therefore be used [64,65]. The use of crude oil is the worst case scenario for the strategic future of the cement industry, although LC³ has proved to be the most robust alternative in terms of profitability while considering energy as operating costs. In order to obtain the best ROCE, the use of the waste + gas combination should be promoted for the production of cement in Cuba, considering that waste management and transport are taken care by the source of the waste and cost nothing to Cuban cement industry. It is clear that in the near future, LC³ technology will help to minimize the uncertainty of costs and benefits within the cement business cycle, even under heterogeneous energy and energy imbalance.

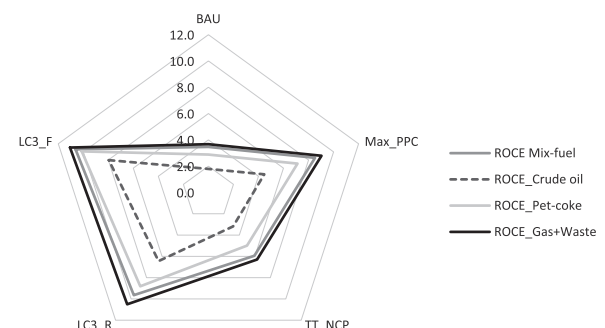


Fig. 11. Sensitivity of ROCE by type of fuel.

6.2. Social value of LC³

LC³ scenario seems to be the most appropriate for Cuban cement industry. They allow a significant reduction of CO₂ emissions per ton of cement, they can meet the fast demand increase and the return on investment becomes higher than the cost of capital (WACC) in the midterm.

The retrofitted option can be implemented faster than the flash calciner option that could be crucial in these very fast changing economical contexts. Finally, both scenario seems to be more robust to unexpected changes in operation costs even if the flash calciner option is the only one to have an elasticity lower than one. Actually, the higher grand total of CAPEX for LC³_F compared to LC³_R is economically compensated by the lower production costs.

In the current hypothesis, we have considered that the price of LC³ will be the same of blended cement (PPC), inducing therefore a higher return on investment due to lower operation costs. However, one could also consider that price of LC³ could be lower. Providing an affordable cement could have direct consequences on the purchasing power of Cuban consumers. Lower material costs on a construction market where materials represent the main costs, as labour is not expensive can have a very direct effect on the economy. Such a choice would have significant social implication, even if it would reduce the ROCE of the cement industry.

The LC³ technology is therefore a technology that allows a debate because the other ones have an already too low ROCE to think about price reduction. LC³ technology could indeed be introduced as a fair technology if the cement price would be adjusted in order to be higher from the WACC from a defined percentage allowing adjusting the cement price accordingly.

As a conclusion, our study shows that LC³ blends present an extremely promising option to achieve lower CO₂ emissions, increase in supply capacity, higher return on investment and potentially lower price on the construction market.

7. Conclusion

The development of alternative cement in developing countries is facing a triple challenge: a very fast increase in demand due to population as well as economic rise, low capital investment possibilities in an economic market with risky perspectives and a need to mitigate greenhouse gas emissions. In this constrained context, this study has shown that LC³ represent a grounded alternative.

Among the available possibilities in Cuba, LC³ technology is the only one who is able to face the demand and maintain a Return On Capital Employed (ROCE) above the expected Weighted Average Cost of Capital (WACC). This economic advantage is more robust than in the other scenario due to a lower sensitivity to operation costs.

Finally, this technology has the potential to be a fair technology if the lower capital investment and the lower operation costs are used to have a viable return on investment for capital invested as well as a lower cement price in order to share the economic benefit of this technology between cement industry and Cuban society.

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