

# Environmental and Economic Sustainability Aspects in Lime-Based Construction Materials

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**Abstract.** Lime-based construction materials (LBM) range from concrete blocks to mortars and plasters used in building new structures or to conserve our cultural heritage. However, little interest has been aroused in the scientific community about their sustainability assessment through Life Cycle Assessment. This research presents a case study carried out within the framework of the SUBLime Project (MSCA ETN-ITN network) and aims at contributing to the understanding of environmental and economic sustainability of LBM. Through a real case-study, a detailed Life Cycle Inventory was developed to calculate the environmental impact associated to different mixes, use of additives, aggregates, etc. Furthermore, Life Cycle Cost Assessment methodology was used to determine the share of different items in the total cost of the cradle-to-grave production of LBM. A thorough analysis of the combined environmental and economic results are presented along with suggestions regarding mix compositions, aggregates, additives, and critical processes in the production line to achieve more sustainable production of LB materials.

## 1 Introduction

The construction sector is one of the biggest contributors to the current environmental crisis, since its materials are and will continue to be used in tremendous quantities all over the world. For instance, during the last six decades, the produced amount of cement has increased 34 times while meanwhile the world population only 3 times [1]. Even though cement is mostly chosen for massive structures, it is not a solution for all our building needs. The wide variety of construction materials also include lime, one of the oldest building materials, of which its use dates to 7000 BC [2]. Lime-based materials include from concrete blocks to mortars, renders and plasters and are used not only in new constructions but in the conservation of the European cultural heritage [3].

According to EULA report in 2020, the lime and plaster industries represented more than 20 Mt/y consumption with the construction industry holding around 19% of the sales sector (2016)[4]. Evidently, the construction industry has an undeniable role in the scenario of lime consumption. Furthermore, besides hydraulic lime, in the production of mortars, renders, and plasters, there is also the use of different types of cement, silicious and calcareous aggregates, lightweight aggregates, and additives according to the purpose and use of the material. Each one of these can contribute differently to the global environmental performance of the product. For instance, during the production of

calcium oxide (precursor for hydrated lime production) up to 1.2 kg CO<sub>2</sub> eq/kg lime is emitted [5] and in the case of 1 kg of Portland cement this is 0.9 kg CO<sub>2</sub> eq [6], [7]. Different types of hybrid cements with fly ash and slags can reduce the global warming potential (GWP) impact of this material [8]. Along with the binders, additives are incorporated in different proportions, of which the production could also lead to serious ecosystem and health risks and would remain hidden if only the GWP will be considered. However, usually the impact of additives is reported as part of the binder production or, when reported separately, only CO<sub>2</sub>eq emissions are shown and often no conclusions can be drawn in this regard [9], [10].

While extensive research on environmental impact assessment of concrete and cementitious materials has been carried out over the last decade [11]–[15], little interest has been aroused in the scientific community regarding the sustainable assessment of lime-based materials. As a matter of fact, some research articles have addressed their environmental profile through Life Cycle Assessment (LCA) ([16], [17]) while no records of economic assessment (LCC) have been found so far. Moreover, a detailed cradle-to-gate LCA has not yet been thoroughly researched, and generally all the environmental impact is assigned to the raw materials transformation. In this study the definition of ‘gate’ refers to the factory outgoing gate where the product is leaving for sale.

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The main goal of this research article is to quantify (through LCA and LCC) and discuss, through different case studies, two aspects of sustainability (environmental and economic) of lime-based plasters manufacturing, helping producers and stakeholders to identify, through this case study, potential hotspots for optimization in their own scenarios

## 2 Methodology

Life Cycle Assessment methodology is used to quantify and compare the environmental impact due to the manufacturing from cradle-to-gate of a lime-based plaster along with a sensitivity analysis on different parameters. This methodology is defined as “the compilation and evaluation of the inputs, outputs and potential environmental impact of a product system throughout its life cycle” [18]. The research carried out is based on the ISO 14040/44 (2006), and accordingly four main steps are to be performed: definition of goal and scope, inventory analysis, life-cycle impact analysis and interpretation of the results [18]. In addition, the economic aspect is addressed through Life Cycle Cost. This assessment is carried out in parallel to the LCA using the same FU, system boundaries and inventory, including information about a variety of costs [19].

### 2.1 Goal and scope definition

The aim of this study is to quantify the impact of the production of 1 tonne of dry lime-based plaster on the environment (Functional Unit), from cradle (i.e., raw materials acquisition) to the gate of the factory. A specific set of parameters for this material is selected and used for the sensitivity analysis. The LCA should help to identify critical parameters in the manufacturing process.

### 2.2 Inventory analysis

To build the LCI of the reference scenario, the used raw materials, the manufacturing plant (devices and streams) as well as different considerations are based on the operation of a real plant, because of the collaborative work of the industrial partners which are part of the EU SUBLime consortium. When this was not possible, the field research was complemented by calculations, model estimations, and expert opinions to complete and validate the inventory data for materials, energy and costs. The database used for the modelling of the processes is EcoInvent V3.6, which is one of the most complete available for the construction sector [6].

### 2.3 Life cycle assessment & life cycle cost

The software OpenLCA was used to run the calculations. With regards to the Environmental analysis, Impact 2002+ was selected as impact method because it addresses relevant impact categories of importance in the mining industry, such as Resources, Climate Change, Human Health, and Ecosystem quality. These endpoint categories are analysed in this work.

With respect to the Economic assessment, to carry out this analysis, the starting point was the inventory of materials and energy (Section 2.2). The calculations are performed from the producer’s perspective, as the main represented actor in the life cycle, aiming at providing an estimate of the possible production costs and costs of pollutant and emissions. For production costs it is enough to consider the purchase price of materials, resources, and energy [19]. In this research the data related to cost was determined in 2022 through market survey and company perspectives.

## 3 Life cycle inventory calculation

The system boundaries of this study are represented in the flow diagram of Figure 1. This plant is a real case in which only the sand is processed at the factory and the rest of the materials are transported to the facilities, in which they are mixed according to a certain recipe.

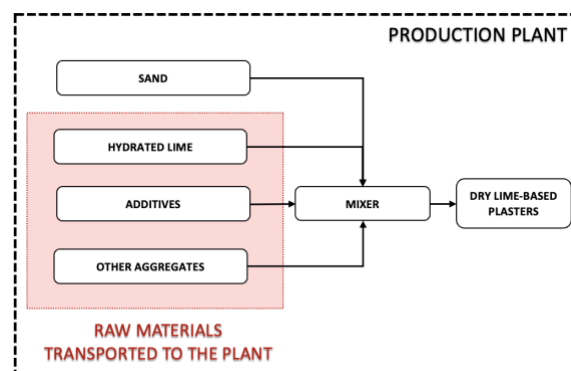


Fig. 1. System boundaries of the study.

### 3.1 Materials and energy inventory

To perform the case-study calculations, in the first place the reference mix composition of a lime-based plaster (with no additives) was investigated. The compositions and the parameters were decided based on the information collected from surveys performed of the lime-based materials producers within the SUBLime project, review of Environmental Product Declarations and reference authors [9], [20]. Because of its soft finishing requirements, as aggregate, the fine fraction of silica sand is used mixed with lightweight aggregates that provides a better and easier coating of the wall. The binder is entirely composed by hydrated lime. Transportation of the fine aggregate is not considered because it is extracted in the vicinity of the plant. Table 1 shows the quantities of the reference scenario. Table 2 shows the main datasets used to model the production of the binders, the aggregates (fine and lightweight), additives and pigments. The abbreviations of each material, mentioned in the manuscript, are specified in Table 2.

**Table 1.** Life Cycle Inventory to produce a lime plaster

|               | Process                      | Amount | Unit | Dataset     |
|---------------|------------------------------|--------|------|-------------|
| <b>Input</b>  | Fine Aggregate (FA)          | 0.675  | t    | Silica Sand |
|               | Lightweight Aggregate (LA)   | 0.07   | t    | Pumice      |
|               | Transportation LA            | 14     | tkm  | Lorry       |
|               | Artificial LA                | 0.005  | t    | Polystyrene |
|               | Transportation Artificial LA | 1      | tkm  | Lorry       |
|               | Hydrated Lime (HL)           | 0.25   | t    | SUBLime [5] |
|               | Transportation HL            | 25     | tkm  | Lorry       |
|               | Dry mixer                    | 4      | kWh  | Germany [5] |
| <b>Output</b> | Plaster P0                   | 1      | t    |             |

**Table 2.** Ecoinvent 3.6 Datasets used to model the production processes and abbreviations

|                              | Process                     | Ecoinvent 3.6 Dataset                                  |
|------------------------------|-----------------------------|--------------------------------------------------------|
| <b>Binder</b>                | Hydrated Lime (HL)          | Laveglia et al. [5]                                    |
|                              | Metakaolin (MK)             | kaolin production, operation and transformation, CH    |
| <b>Coarse Aggregate</b>      | Silica Sand (SA)            | gravel and sand quarry operation, CH                   |
| <b>Lightweight Aggregate</b> | Pumice Aggregate            | pumice quarry operation, GLO                           |
|                              | Perlite                     | expanded perlite production, GLO                       |
| <i>(artificial)</i>          | Polystyrene (PLYA)          | polystyrene production, expandable, GLO                |
| <b>Additives</b>             | Water Retention Agent (WRA) | carboxymethyl cellulose production, powder–RoW         |
|                              | Air Entrainer (AE)          | alkylbenzene sulfonate, petrochemical RoW              |
|                              | Hydrophobic Agent (HA)      | polycarboxylates production, 40% active substance, RER |
|                              | Dispersion Agent (DA)       | ethylene vinyl acetate copolymer production, RER       |
| <b>Pigments</b>              | White Pigment               | calcium carbonate production, precipitated, GLO        |
|                              | Red Pigment                 | portafer production, GLO                               |
| <b>Transportation</b>        | Lorry                       | transport, lorry 16-32 metric ton, EURO6   RoW         |

For the case studies 7 cases were developed. All the cases imply a modification of the LCI of the reference Plaster P0. Only the mentioned parameters in the case are modified, while the rest remain the same as described in Table 1.

- P1: replacement of 7% of Hydrated Lime by Metakaolin.
- P2: total replacement of perlite by polystyrene fibres as artificial lightweight aggregate.
- P3: increment of the lightweight aggregate from 7% to 14% (7% decrement of fine aggregate)
- P4: no transportation distance of hydrated lime (0 tkm)
- P5: incorporation of additives to the mix (referred to the binder in mass proportions: 2.5% Dispersion Agent, 0.20% Water Retention Agent, 0.02% Air Entrainer, 0.3% Hydrophobic Agent, 0.5% White Pigment). Average transportation distance per additive 250 km.
- P6: same as P5 but change in the pigment from white to red.
- P7: same as P5 but increased average transportation distance per additive to 500 km.

### 3.2 Costs inventory

Three main categories can be generalized: (a) Direct production costs (raw materials, energy purchase, etc.); (b) Indirect cost (treatment of industrial residues, etc.); and (c) Externalities (associated to the taxes for emitting a certain pollutant, such as CO<sub>2</sub>). The total costs are usually the summatory of the initial costs, the operating costs, and the end-of-life costs. In this study and for the LCC calculation, direct production costs and externalities are considered.

With respect to the direct costs, in this study the focus is on variable costs (excluding fixed costs, e.g., initial costs, purchase of equipment, salaries, total taxes, etc.). The following variable production cost elements are included:

- Purchase of raw materials transported to the plant (for the reference mixes and the scenario analysis)
- Transportation costs associated to the purchase of the raw materials
- Electricity consumption in the mixing plant (all the devices included in the system boundaries)

To account for externalities, the carbon price in the context of the European Emission allowance is considered. The price of emission allowances has increased from below 10 € per metric ton of carbon, to above 90 € since the beginning of 2018 [21]. As a mean of comparison and to evaluate the effect of the carbon pricing on the total cost assessment, the two values reported by the European Central Bank for 2018 (10 € per metric ton of carbon) and 2022 (90 € per metric ton of carbon) are considered in the LCC calculation [22].

**Table 3.** Life Cycle Cost Inventory

| Group                          | Item                 | Unit   | Cost |
|--------------------------------|----------------------|--------|------|
| <b>Binders</b>                 | Hydrated Lime        | €/kg   | 0.11 |
|                                | Metakaolin           | €/kg   | 0.15 |
| <b>Aggregates</b>              | Sand                 | €/kg   | 0.01 |
|                                | Pumice               | €/kg   | 0.06 |
|                                | Expanded perlite     | €/kg   | 1.77 |
|                                | Polystyrene          | €/kg   | 1.29 |
| <b>Additives</b>               | CMC                  | €/kg   | 0.97 |
|                                | ABS                  | €/kg   | 0.80 |
|                                | PCX                  | €/kg   | 0.65 |
|                                | EVA                  | €/kg   | 1.12 |
|                                | CC                   | €/kg   | 0.45 |
|                                | Iron oxide           | €/kg   | 0.01 |
| <b>Transportation</b>          | Truck transportation | €/t.km | 0.06 |
| <b>Electricity consumption</b> | Electricity          | €/kWh  | 0.11 |

## 4 Life cycle impact assessment

Figure 2 shows the results of the life cycle assessment and the effect of the selected parameters on the impact indicators.

In order to have a better understanding of the sharing in the magnitude of the impact indicator, six categories have been created: Cement Production, Hydrated Lime Production, Sand Production, Additives & Aids Production, Total Transportation and Plant Operation. The first four categories refer to the production of the materials from the cradle to the gate of the corresponding production plant (e.g., cement plant). Total Transportation summarizes all the transportations of the raw materials to the plant and Plant Operation refers to the electricity required to operate the plant.

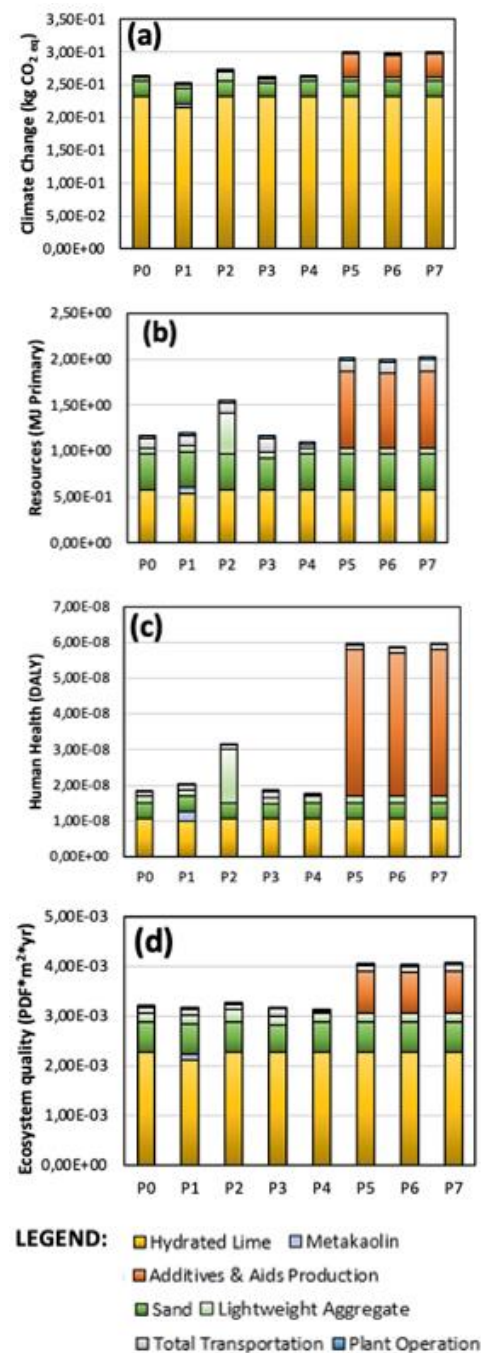
### 4.1 Climate change

In terms of the binder production, Hydrated Lime dominates the GWP indicator and contributes up to 80% (Figure 2a). Meanwhile, Metakaolin is not a significant contributor to this indicator. The average contribution of the additives is around 14 %, being the water retention agent and the dispersion agent the most significant contributors.

### 4.2 Resources

In the case of Resources category (Figure 2b), what must be highlighted is the case P2, in which 5% of the perlite Lightweight Aggregate is replaced by expanded polystyrene. The first one is a natural lightweight aggregate that does not need an intensive processing, meanwhile the second one is the result of an industrial process with a relevant environmental impact [23]. The results shows that this indicator can increase up to 33% due to the use of polystyrene instead of perlite. The inventory reveals that the process intensity of

polystyrene is around 89 MJ primary/kg and for perlite it is 13 MJ primary/kg of Perlite, around 7 times difference. In the case of the additives, a similar situation occurs as described for the mineral extraction indicator. In the case of P7, around 60% of the indicator is dominated by the additives production. In particular, the main contributors are WRA (69%), DA (21%), followed by AE (7% and process intensity 0.08 MJ primary/kg). None of the pigments used in the plaster contribute significantly to the indicator.



**Fig. 2.** Life Cycle Assessment Impact results for the reference scenario and the scenario analysis

### 4.3 Human health

In Figure 2c, there are two important cases to highlight: P2 and P5 to P7. In the first case, it is highly relevant to



notice that even a small proportion (0.5%) of the used artificial lightweight aggregate polystyrene in replacement of the perlite, has a huge impact on the indicator, representing around 44% of it. The second case (P7) is featured because increments of around 200% with respect to the reference case P0 are recorded. In general, the additives production represents 70% of the total indicator (P7). The main contributor is Ethylene Vinyl Acetate production, followed by Carboxymethyl Cellulose and lastly with a shared place of importance polystyrene and Alkylbenzene Sulfonate production. The use of additives has an important impact, due to the emissions during the production process. This shows the importance of moving towards bio-based products to obtain eco-friendlier additives for construction materials. It is fundamental to find alternatives for WRA and DA because the indicators considered have proven to be highly sensitive to them.

#### 4.4 Ecosystem quality

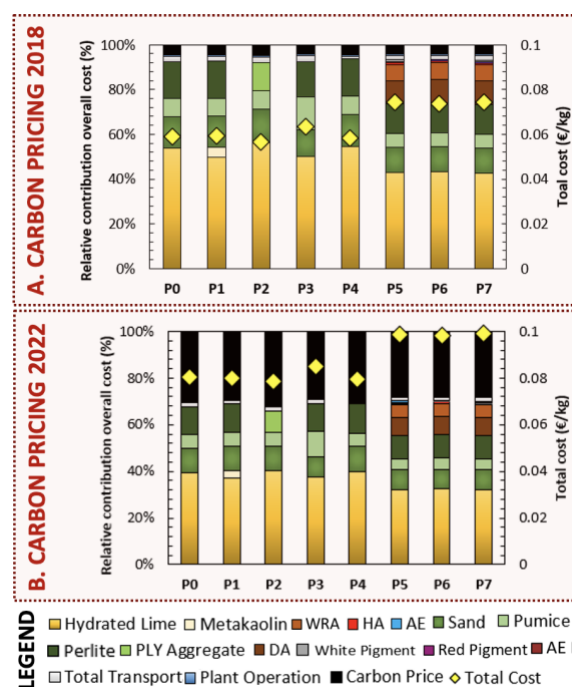
Finally, regarding the Ecosystem quality endpoint category (Figure 2d), the binder remains the most significant contributor to the indicator. Seeing the significant relative weight of the fuel and electricity mix on the binder production, the importance of switching to eco friendlier energy sources to obtain a balanced reduction on the indicators must be stressed once more [5]. It is also interesting to show that even though the use of metakaolin can lead to better mechanical properties, it does not have a meaningful contribution to reduce the impacts in this category. However, special attention should be given to the polystyrene. The indicator has proven to be sensitive to its proportion. Previous comments about the need for searching for new types of water retention agents, are still valid.

### 5 Life cycle cost assessment

In Figure 3 the results of the economic assessment for plasters in the scenario (A) with carbon pricing 2018 (10 € per metric ton of carbon) and scenario (B) with carbon pricing 2022 (90 € per metric ton of carbon) are presented. The graphs show on the left axis the relative contribution of the cost components in the overall cost and in the right axis the total cost. All the items of the direct cost production associated to the raw material purchase, transportation, plant operation (electricity consumption) as well as the externalities (carbon pricing) have been disaggregated for a better analysis of the relative contribution.

When the carbon pricing in 2018 is considered, in general it is observed that its contribution for all analyzed cases is around 5-10% of the total cost. With respect to the binder's contribution, they account for around 50 to 60%. Total costs vary between 0.06-0.08 €/kg. Furthermore, including metakaolin in the binder mix does not modify severely the cost, with the consequence of a potentially better mechanical performance (P1). Replacing the production of perlite by PLYA slightly lowers the total cost. However, the

large environmental impact associated to its production has been discussed previously. The total cost of the additives production is almost the same as the total aggregate cost (20% of the relative contribution).



**Fig. 3.** Life cycle cost assessment results considering the effect of carbon pricing in 2018 (A) and in 2022 (B).

In the scenario B the effect of the sudden change on carbon pricing is evaluated (from 10 to 90€ per metric ton of carbon). As previously discussed from 80 to 90% of the emissions in plasters are attributable to the binder's production, with a release of up to 0.32 kg CO<sub>2</sub> eq/kg of plaster. Therefore, the total costs experience roughly an increment 30% respectively.

There are two main relevant outputs of this simple case study. On the one hand, in the building materials business, accounting for externalities is critical in the context of a very turbulent market. On the other hand, for a sustainable production it is decisive to have a closer look at the cradle-to-gate emissions, to reduce the environmental impacts and costs. New technologies such as on-site carbon capture, fuel savings by using highly efficient kiln technologies, improving the use of waste heat, among others, are alternatives being considered in the lime industry [3]. However, the achievement of these goals requires the commitment of all involved parties, from producers to policy makers and customers.

### 6 Conclusions

In this research work the environmental and economic life cycle assessment to produce lime-based plasters from cradle-to-gate have been analysed. The following conclusions can be drawn:

### Environmental impact assessment:

- Climate change: up to 0.32 kg CO<sub>2eq</sub> per kg of plaster is released. Around 70 to 80% of the GWP is dominated by the binders' production, followed by the coarse aggregate (15-20%) and additives production (10%).
- Resources: A key role in this indicator is played by the binders (25-50% of the indicator) and the coarse aggregate (15-50% of the indicator).
- Human health: highly sensitive to organic polymers as lightweight aggregate. The use of additives can contribute up to 70% of the indicator and account for as much as three times the sum of the binder and aggregate production.
- Ecosystem quality: the binder remains the most significant (60-80% of the indicator). Previous comments about the need for searching for new additives for water retention agents, are also valid here.

### Economic impact assessment

- In general, in 2018 the total costs are distributed between binders (40-55%), aggregates (25-30%), additives (15%) and carbon pricing (10%). The results are severely affected by a change in 2022 of the carbon pricing. Because of the CO<sub>2</sub> eq emissions of plasters production, the total costs exhibit an increment of about 30% in 2022. The share of the carbon pricing on the 2022 total cost can be up to 40%.

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