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Environmental footprint study of mortars, renders and plasters formulations with no, low or high hydrated lime content

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ABSTRACT: A comparative environmental assessment study focusing on the stages of mortar production and carbonation through hardening has been conducted by the European Lime Association in collaboration with mortar producers from various EU countries on 17 formulations of mortars, renders and plasters. The results of the "cradle-to-gate" for mortar and renders indicated that: 1. There are no significant differences between products with low and high lime contents and 2. Depending on the lime content in the products, the contribution of the hydrated lime to the different environmental indicators can range between 0% and about 20%; 3. The differences in the environmental impacts of mortars and renders produced in integrated or non-integrated mortar plants are generally rather small. However, there are clear differences in the environmental footprints of gypsum or lime based plasters: 1. based on the plaster composition investigated in this study, it appears that lime based plasters have the lowest environmental footprint for some of the impacts (primary energy consumption, abiotic depletion and water eutrophication), whereas for the remaining indicators the gypsum based plasters have the lowest environmental footprint. The lime carbonation process lowers the overall carbon footprint during the first period of the use phase of the mortars in buildings. This impact shall be taken into account in holistic LCA studies. If not, this leads to a wrong interpretation of the environmental impact of the mortars.

Keywords: Environmental footprint; comparative assessment; mortars; renders; plasters; lime

1 INTRODUCTION

The life cycle assessment (LCA) studies of the of construction materials and their use in buildings has been increased over the last years due to the pressure on primary raw materials and the agenda on the climate change around the world. Conducting LCA studies is a tedious task, since the availability of data and their overall quality (average data, country specific data, site specific data) hampers the overall quality of the studies therefore simplistic approaches might be necessary in order to perform an LCA for building materials in order to allow an overall LCA assessment. The LCA studies asses assessing the impacts when selecting products for their overall performance and minimise the environmental impact during the manufacturing, transport, construction, maintenance, refurbishing and end of life phases of a building.

A literature review [1] carried out on 60 studies covering 9 countries (including Sweden, Germany, Australia, Canada and Japan) indicated that the proportion of embodied energy in materials used and life cycle assessed varied between 9% and 46% of the overall energy used over the building's lifetime

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when dealing with low energy consumption buildings (with good insulation, adequate orientation, passive conditioning, etc.) and between 2% and 38% in conventional buildings with a lifetime ranging from 25 to 100 years. Often, products that are presented as cheap in the medium term might result in high maintenance or waste management costs. Contrarily, it may be that when considering the whole life cycle, materials with significant CO_2 emissions, such as concrete or lime, can see their emissions reduced by their lower maintenance requirement, higher durability and giving them a second life as a filler material in infrastructure (concrete), with a double effect: the reduction of emissions compared with obtaining raw materials from quarries and the absorption of CO_2 due to the carbonation processes (lime) [2]. Figure 1, provides an overall view of the various materials used in construction and their primary energy demand and CO_2 manufacturing footprint [3]. Therefore, as suggested [2] it is fundamental to conduct holistic LCA studies and Life Cycle Cost Assessments (LCCA) in order to account both the environmental footprint and overall costs when identifying the most environment friendly technology. In the opposite case, this could lead to wrong conclusions and choices with regards to the materials used in the project.

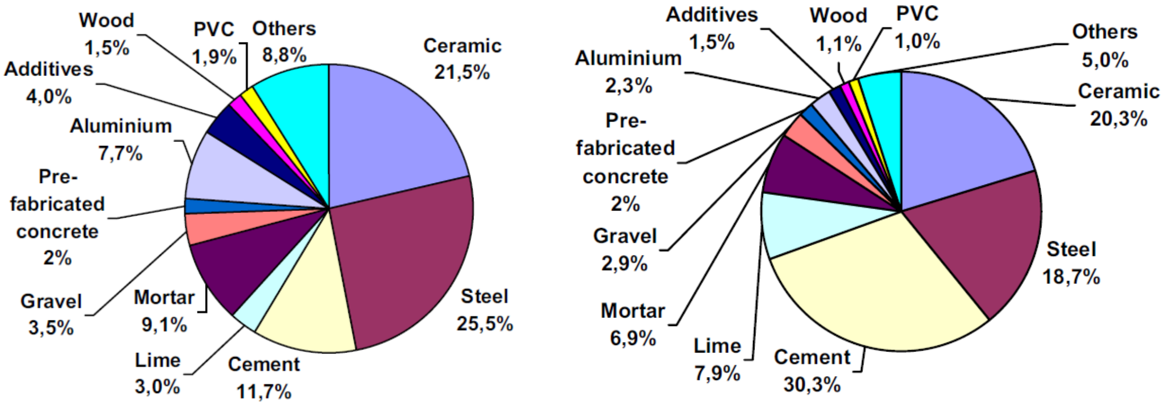

Figure 1. Contribution of (a) primary energy demand (b) CO_2 emissions associated with the manufacture of the materials needed for the construction of 1 m² (gross floor area). Results from [2]

The term "lime," in spite of being used broadly and loosely, refers to a product derived from limestone in an industrial process known as calcination. Naturally occurring limestone, which is composed almost exclusively of calcium carbonate [$CaCO_3$], transforms into quicklime (reaction 1) by applying heat (Boynton 1980) into a process known as calcination at high temperature in kilns. When slaked with water, quicklime transforms into hydrated lime (reaction 2).

Quicklime reaction: $CaCO_3 + \text{heat} \rightarrow CaO + CO_2$ (*1*)

Hydrated lime (known as slaked lime), reaction: $CaO + H_2O \rightarrow Ca(OH)_2$ (2)

Lime products are versatile materials that are used in many different applications, e.g. in steel, agriculture, paper, chemical, environmental protection, civil works, mortars, etc. Lime has been used in construction for millennia, and its value, especially in the field of conservation architecture, has been revived during the recent years due to the functionality and the natural CO_2 absorption known as the carbonation or hardening process as shown in various research papers for mortar [4-11], for steel [12] .Mortar for masonry mortar standards define the use of in the application covered in this case-study, are described in the EU standards EN998-2 [26] any Cement-lime mortar combinations are defined in the ASTM C-270 [13] standard for mortar for masonry

This paper presents the results of a comparative environmental footprint study [25] comparing the masonry mortars, lime-cement plasters and gypsum plaster with no, low or high amount of hydrated lime using the environmental impact methodology defined within the LCA standard series 14040-14044 [14, 15]. The aim is to acquire knowledge on the environmental footprint of these building materials for the life stages of manufacturing and carbonation for formulations used in Europe.

2 METHODOLOGY

2.1. Scope of the study & system boundaries

The scientific and quantitative approach is based on the LCA standards defined in the ISO 14040 - 44 series [14, 15]. According to the LCA standard series a LCA study shall enable quantifying the different environmental impacts along the whole life cycle of a product as shown in Figure 2. However when the study was launched, it appeared that some of the key information needed for developing the LCA model for the following stages packaging, transportation to the end users, use phase (excluding carbonation and end of life was in not available. Therefore the objective of the study was redefined as follows:

Comparative assessment enabling to highlight the differences in the environmental impacts between various types of mortars, renders or plasters, and assessment of the sensitivity of some parameters (e.g. lime content) on the results, based on following life cycle stages:

1. Bulk production of mortars, renders or plasters from the cradle to the gate of the mortar plant and 2. Hardening (carbonation) of these products during their lifetime.

The comparative assessment is aiming to follow the ISO 14040 /44 standards as closely as possible, however since some life cycle stages are not modelled and their impacts not quantified, the term "comparative environmental footprint study" will be used throughout the paper instead of "comparative LCA".

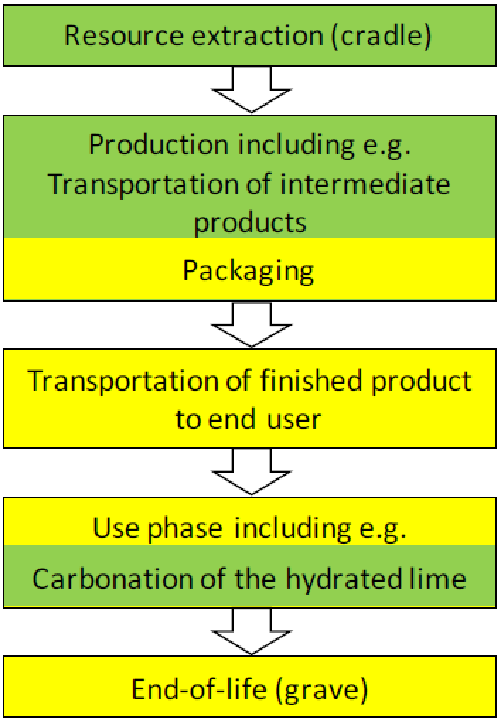

Figure 2. Life cycles stages of the products in the scope of the study (green) and the identification of the data gaps (yellow).

The environmental footprint is calculated for each of the 17 formulations (Table 1) being used in various EU countries and the results will be shown for each of the formulations investigated.

Table 1. List of the products in the scope of the environmental footprint study.

Product description	Products in the scope of the study					
	Masonry mortars		External Renders		Internal Plasters	
	With lime	**Without** lime	**High** content of lime	**Low** content of lime	Lime cement plasters	Gyspum plasters
Compresive strength of selected products	M5 6 - 8 MPa	M5 6 - 8 MPa	CSII	CSII	-	-
No of products investigated in this study	4	3	2	3	3	2

The core process modelled in the study is the manufacturing of the 17 products defined in Table 1. The boundaries of the system considered for the production phase are shown in Figure 3 and it includes: 1. The production of the raw materials needed to manufacture the products (Sand, Hydrated lime, cement, gypsum (depending on the type of product), Mineral and chemical additives; 2. The transport from their respective production sites to the mortar plant; 3. The mixing of the materials in the mortar plant. The process is the same irrespective the product considered (e.g. mortar, render or plaster). To be exhaustive, the generation of waste is displayed on the Figure 3 although reliable data could not be found for all the processes.

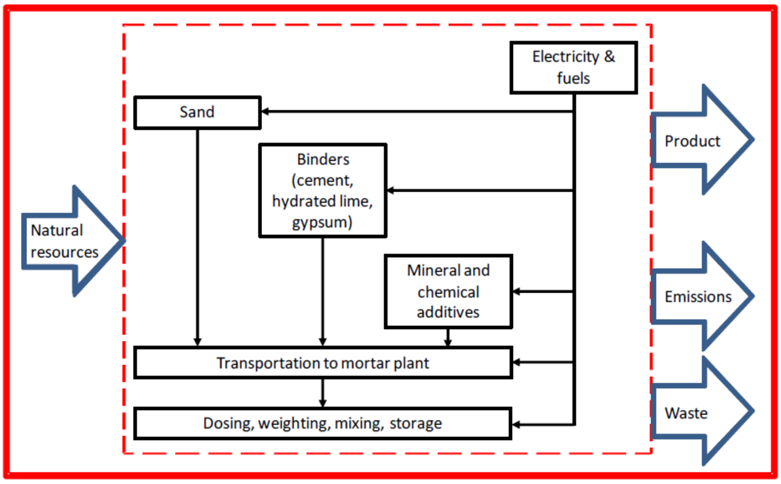

Figure 3. System boundaries for the production phases of mortars, renders and plasters

2.2. Data sources

Production of sand: The manufacturing of the sand entering in the composition of the products was modelled by using different LCI datasets which refer in all cases to average German conditions. Indeed there is no equivalent LCI available for average European conditions. Thus the following LCI's were included in the model:

- Limestone sand & limestone filler: four different LCI's were used from the PE / Gabi 5.0 database [16] in order to take into account the different grain sizes of the sands used, i.e. limestone sand/filler with an average grain size of: a) 2 mm; b) 1 mm; c) 0.5 mm; d) 50 µm. If no detailed information about the type of limestone sand was provided, it was assumed that: a) the "limestone sand" consists of a 1 mm sand; b) the "limestone flour" consists of a 50 µm sand.
- Quartz sand or silica sand (0/2) from the PE / Gabi 5.0 database [16].

Production of Hydrated lime: The data used for modelling the production of hydrated lime are based on the Life Cycle Inventory that was carried out for the European Lime Association and completed in 2011 [17, 18].

Production of cement: Different types of cement are entering into the composition of mortars, renders or plasters. If the cement consisted of Portland cement (CEM I), the manufacturing of the cement was modelled by using the LCI dataset from the ELCD database [19] that represents average European conditions for the production of CEM I.
For other cement qualities, LCI's are not available in the ELCD database. For the cements of type CEM II, French LCI's [20] were used to derive a "LCI equivalence" factor between CEM I and CEM II cements. This factor was calculated as follows:

- For each in- and output flow: determination of an average flow representing the various types of CEM II cements,
- For each in- and output flow: division of the previously calculated average flow with the corresponding flow for CEM I,
- Determination of the "LCI equivalence" factor as the average of the ratios calculated in the previous step. In practice it appeared that most of these ratios were similar and close to the "LCI equivalence factor", i.e. 0.82.

Finally as a proxy for the LCI of European CEM II cements, the LCI dataset of CEM I from the ELCD database was multiplied by the factor 0.82. For other very specific type of cements for which no LCI was developed, the equivalence factor was determined by dividing the specific energy consumption needed (and / or the specific CO2 emission) for the production of these cements with the respective values for CEM I. As a proxy, the LCI data of these types of cement was then determined by multiplying the in- and outputs flows of CEM I with the calculated equivalence factor.

Production of gypsum: Gypsum is entering into the composition of some plasters. In this case, the production of gypsum was modelled by using the LCI dataset of gypsum plaster from the ELCD database [19] that refers in fact to German average conditions. In this LCI, the gypsum consists of a mix of calcium sulphate beta semi-hydrate ($CaSO_4 \cdot ½ H_2O$) produced from natural gypsum (45%) and gypsum generated during the flue gas desulphurisation (FGD) of power plants (55%).

Production of mineral and chemical additives: The production of all mineral and chemical additives that are mixed with the sand and binders were modelled with the PE / Gabi 5.0 database [16] and a special extension of this database (i.e. the "Building Material" database).

At the request of EuLA, the inputs for the production of mortars were based on the information mentioned in the report [21] for the production of dry mortar. The assumptions for the energy consumption are summarized in Table 2.

Table 2. Energy consumption for the production of mortars

Flows		Unit	Dry mortar
Inputs	Electricity	kWh / kg	0.109
	Thermal energy from nat. gas	MJ / kg	0,038
	Thermal energy from LFO	MJ / kg	0.008
	Diesel	kg / kg	2.18×10^{-5}
	Compressed air	Nm^3 / kg	0.038
	Lubricants	kg / kg	1.05×10^{-6}

For the transportation, two scenarios were considered for the modelling (Table 3):
1. Base case: mortars, renders or plasters are produced in integrated plants (extraction and processing

take place in the same location for limestone sand, the hydrated lime and the mortars, therefore the transport distance is negligible). In this case, it was assumed that the transportation distances of the raw materials apart from limestone sand, hydrated lime and cement are the same than those defined in the report [21]. Based on specific information provided by EuLA members, a reduced transportation distance was assumed for cement. No transportation for the limestone sand and the hydrated lime was taken into account in this case. Furthermore it was assumed that that all goods are transported by articulated lorries (Euro 4 – trucks) with a payload of 27 t. The corresponding dataset has been provided by the Gabi 5.0 database [16].

2. Alternative case: mortars, renders or plasters are produced in non-integrated plants, thus meaning that the limestone sand and the hydrated lime have to be transported respectively from a limestone quarry and from a lime plant.

Table 3. Transportation distances of the raw materials for integrated and non-integrated plants

Base case	**Unit**	**Base Case: Integrated plants**	**Alternative case: Non integrated plants**
Limestone sand	km	0	210
Quartz sand	km	100	100
Hydrated lime	km	0	250
Cement	km	95	95
Gypsum	km	300	300
Other mineral or chemical additives	km	300 to 500	300 to 500
Norm	**-**	Truck Euro 4 with payload of 27 t	

2.3. Carbonation of the mortars, renders, plasters

From the different tests aimed to determine the carbonation levels of lime based mortars [4 to 11], it can be concluded that on the long term the carbonation level is typically ranging between 80% and 97.5% depending on the type of mortars. Since the carbonation of the calcium hydroxide is mainly driven by the diffusion rate of the CO2 in the mortars, it can be realistically assumed that the long term carbonation levels are higher in thin render or plaster layers than in thicker sections of masonry mortars. In this study [25], no distinction was made in the carbonation level between mortars, renders and plasters. The following constant value was therefore used:

- Assumed long term carbonation level in lime based products: 90%, thus leading to a calculated CO2 sequestration of 0.535 kg CO2 / kg hydrated lime included in the product
- From the few available literature sources about carbonation of cement based mortars [22, 23, 24], it can be concluded that the carbonation level in this type of products is usually ranging between 20% and 25%. Therefore the following constant value was used in the study: Assumed long term carbonation level in cement based products: 22%, thus leading to a calculated CO2 sequestration of:
  - 0.093 kg CO2 / kg CEM I included in the product
  - 0.074 kg CO2 / kg CEM II included in the product

3 RESULTS

3.1. Overall environmental impacts for mortars

There are no significant differences in terms of environmental footprint between cement and lime based mortars as can be seen in Table 4.

Table 4. Selected environmental indicators for cement and lime based mortars

Category	Unit	Average cement based mortar	Average lime based mortar	Δ (LI-CE)/LI
Primary energy consumption	MJ/t	1 989	1 887	-5,40%
Abiotic resource depletion	kg Sb/t	0,676	0,624	-8,30%
Global warming potential **without** inclusion of the long term carbonation	kg eq CO_2/t	180	189	+4,7%
Air acidification	kg eq SO_2/t	0,553	0,550	~0,6%
Photochemical oxidant formatio	kg eq C_2H_2/t	$4{,}47 \times 10^{-2}$	$5{,}00 \times 10^{-2}$	+10,7%
Stratospheric ozone depletion	kg eq R111/t	$8{,}75 \times 10^{-6}$	$8{,}90 \times 10^{-6}$	+1,7%

3.2. Overall environmental impacts for renders

As can be seen in Table 5, the differences in the environmental footprint of renders with low and high lime contents are rather limited, i.e. they do not exceed 15%. Renders with higher lime contents lead always to an increase of the environmental impacts except for the stratospheric ozone depletion. See also Figure 4 B, for the differences between the integrated and non-integrated plants.

Table 5: Selected environmental indicators for renders with low and high lime contents

Category	Unit	Average cement based mortar	Average lime based mortar	Δ (LI-CE)/LI
Primary energy consumption	MJ/t	1 978	2 220	+10,9%
Abiotic resource depletion	kg Sb/t	0,655	0,770	+14,8%
Global warming potential **without** inclusion of the long term carbonation	kg eq CO_2/t	189	209	+9,5%
Air acidification	kg eq SO_2/t	0,576	0,579	+0,7%
Photochemical oxidant formatio	kg eq C_2H_2/t	$5{,}16 \times 10^{-2}$	$5{,}67 \times 10^{-2}$	+9,2%
Stratospheric ozone depletion	kg eq R111/t	$10{,}2 \times 10^{-6}$	$8{,}94 \times 10^{-6}$	~14,2%

3.3. Overall environmental impacts for plasters

Unlike mortars and renders, the differences between gypsum based and cement-lime based plasters in a cradle to gate approach are much more important as highlighted in Table 6. For the impact categories: 1. Primary energy consumption; 2. Abiotic depletion; 3. Eutrophication and 4. Freshwater toxicity, the lime based plasters have the lowest environmental footprint, whereas for the remaining indicators the gypsum based plasters have the lowest environmental footprint. See also Figure 4 C, for the differences between the integrated and non-integrated plants.

Table 6: Selected environmental indicators for plasters with low and high lime contents

Category	Unit	Average cement based mortar	Average lime based mortar	Δ (LI-CE)/LI
Primary energy consumption	MJ/t	3 540	2 558	~38,4%
Abiotic resource depletion	kg Sb/t	1,40	0,91	~53,3%
Global warming potential **without** inclusion of the long term carbonation	kg eq CO_2/t	202	265	+24,0%
Air acidification	kg eq SO_2/t	0,597	0,627	+4,8%
Photochemical oxidant formatio	kg eq C_2H_2/t	$1{,}82 \times 10^{-2}$	$6{,}77 \times 10^{-2}$	+73,1%
Stratospheric ozone depletion	kg eq R111/t	$6{,}32 \times 10^{-2}$	$10{,}2 \times 10^{-6}$	+37,9%

3.4. Carbonation rate for the mortars, renders and plasters

Before carbonation, the GWP of lime containing mortars is in average slightly higher (approximately 5%) than the GWP of pure cement based mortars (low or no lime content). However due to the higher potential of lime based mortars to capture CO_2, part of the hardening proces of hydrated llime, the order of the results is changed in long term. The GWP of lime based mortars is then slightly lower (-3%) than the GWP of cement based mortars.

If the carbonation is considered, the calculation shows that the GWP's of the renders with the lowest and the highest lime contents become almost equivalent. Carbonation is calculated to take 1 to 3 years depending on their thickness (scenario of 2-3 cm) [5, 9].The difference in the GWP's between the two renders becomes then less than 0.5% in favor of the render with the highest lime content.

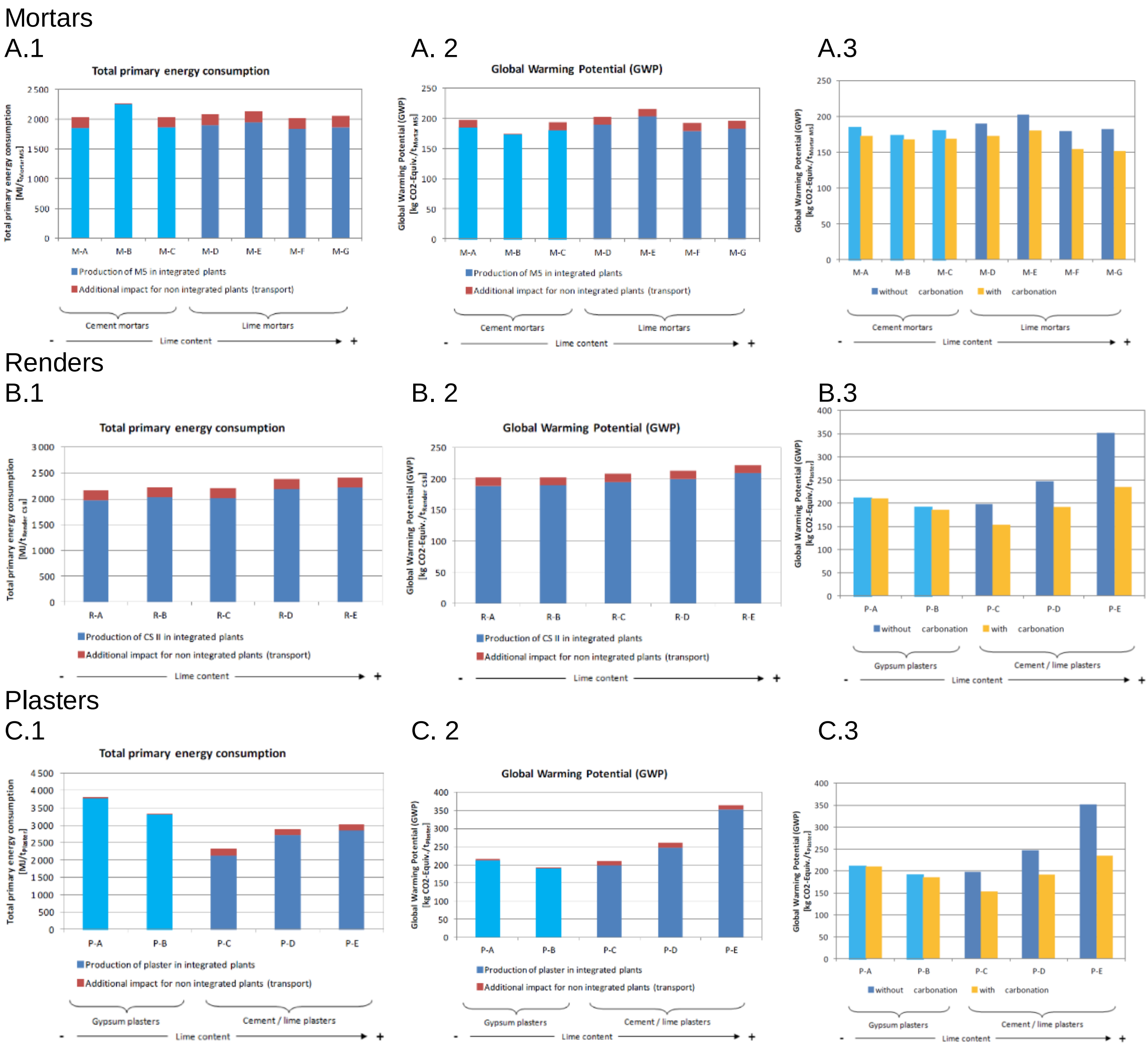

Figure 4: Selected environmental impacts for mortars, renders and plasters.

If the carbonation is considered, the calculation shows that the GWP's of the lime based plasters become equivalent to those of gypsum based plasters The difference in the GWP's between the two types of plasters becomes then less than 2.5% in favour of the lime based plasters. Figures 4 A3, B3 and C3 provides a corrected global warming potential when the carbonartion rate is amended accordingly (90% for lime and 22% for cement) as explained in section 2.3

4 CONCLUSIONS

The key outcome of the study is:
For mortars and renders:

- In terms of environmental footprint, there are no significant differences between products with low and high lime contents.
- Depending on the lime content in the products, the contribution of the hydrated lime to the different environmental indicators can range be-tween 0% and about 20%.
- The differences in the environmental impacts of mortars and renders produced in integrated or non-integrated mortar plants are generally rather small.
- The influence of the carbonation of the products which are fundamentally a part of the lime hardening kinetics on their Global Warming Potential (GWP) is logically the highest for products with higher lime content. Such products have usually higher GWP's at the gate of the mortar plants. However, on the long term (notwithstanding the conservative assumption about the carbonation level used in the study), their carbon footprint becomes after the hardening phase (use phase) slightly better than those of products with low(er) lime contents.

For plasters

- There are clear differences in the environmental footprints of gypsum or lime based plasters.
- Based on the plaster composition considered in this study, it appears that lime based plasters have the lowest environmental footprint for primary energy consumption, abiotic depletion and water eutrophication, whereas for the remaining indicators the gypsum based plasters have the lowest environmental footprint.
- Depending on the lime content in the plasters, the contribution of the hydrated lime to the different environmental indicators can vary in a wide range, i.e. between 0% and 40%.
- The differences in the environmental impacts of plasters produced in integrated or non-integrated mortar plants are generally rather small.
- Lime based plasters have generally higher GWP's than gypsum based plasters if the long term carbonation is not considered. However this out-come changes whit the inclusion of the carbon sequestration during the hardening process. Then lime based plasters have an equivalent or even better carbon footprint.

The results of the study can be used for improving knowledge and providing guidelines for materials selection in the design of new buildings and refurbishment of existing ones.

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