Life cycle assessment of natural and recycled gypsum production in the Spanish context

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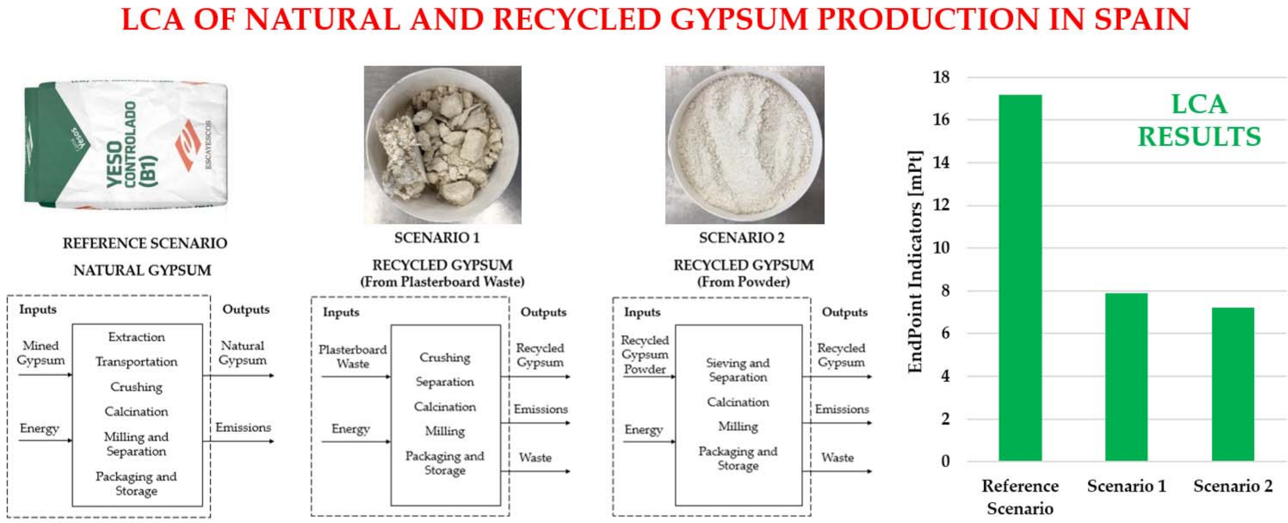
ABSTRACT

Spain occupies a very prominent position as a world producer of gypsum. Consequently, the industrial processes are more refined, as the production volumes of the factories are much higher than in other countries. Therefore, the environmental impacts of the production of one ton of gypsum are significantly lower. However, new cleaner alternatives must be studied to promote more sustainable construction. In that sense, this paper aims at studying the environmental assessment of the production of natural and recycled gypsum in the Spanish context. In order to conduct the environmental analysis, a from cradle to gate life cycle assessment (LCA) was carried out, using the Impact 2002+ methodology. All the input data was obtained from a medium-size gypsum manufacturer located in Jaen (Andalusia), one of the best regions in terms of gypsum purity. The results for all the scenarios under study were analyzed separately and compared with previous studies published by other investigators and manufacturers' reports data. Contrary to most other previous researches, the LCA was performed on the basis of primary data given by the producer, and the regional factors were also taken into account.

The results achieved in the LCA showed for the production of recycled gypsum (from plasterboard and powder waste) a significant improvement (more than 40%) in all the impact categories understudy, as compared to the natural gypsum production. Furthermore, the results obtained for the endpoint indicators showed an important reduction (56 and 58%) of the environmental impacts when recycled gypsum production was compared with the natural one. On the other hand, it was reaffirmed that the natural gypsum production process in Spain is less environmentally harmful than in other countries.

Keywords: Gypsum waste; recycled gypsum; environmental impact; LCA; waste utilization.

GRAPHICAL ABSTRACT



HIGHLIGHTS

- The LCA of natural and recycled gypsum production in Spain is presented.
- A reduction (56 and 58%) of the environmental impacts was achieved for the recycled gypsum scenarios.
- The natural gypsum production in Spain is less harmful than in other countries.
- The recycled gypsum in powder showed the best environmental/mechanical performance.

1. INTRODUCTION

There is a growing concern about carbon emissions and their effects on the environment, climate change and human health (Mikulčič et al., 2016). In this regard, the building sector is one of the major responsible for these emissions (Bigerna et al., 2017), which forced the emergence of various regulations and guidelines to reduce these harmful effects on the environment (Pacheco-Torgal, 2014). Architects and civil engineers should use and develop new construction materials in a way that reduces the environmental impacts their production has on the planet. Thus, many researchers have used several methodologies to evaluate the environmental assessment of buildings and construction products, being life cycle assessment (LCA) one of the most developed (Hossain and Ng, 2018). In that sense, although gypsum is one of the least environmentally harmful coating materials compared to cement mortars (Chen et al., 2010), the process of obtaining it can still be greatly purified to substantially reduce the impacts they generate.

Gypsum is a very abundant material in the world and it is used mainly in the construction sector (plasters for renderings, plasterboards, prefabricated blocks, etc.). It is a versatile material, thermal insulator, humidity regulator, incombustible and acoustic absorber (De Brito and Flores-Colen, 2015). Spain, as it is shown in Figure 1, continues to occupy a very prominent position as a world producer of gypsum (Escavy et al., 2012; Herrero et al., 2013), and maintains its position in the European market as a production leader, as well as the main exporter (Reichl et al., 2018). In 2016, 89 gypsum exploitations were active in Spain, of which a total of 8,936 kilotons of gypsum were obtained (IGME, 2018). As the amount of natural gypsum obtained in each country varies significantly depending on the presence of this mineral in their geology, the production of natural gypsum also shows some variations. In countries with higher annual production, such as China or Spain, the industrial processes are more refined, as the production volumes of the factories are much higher than in other countries. Therefore, this fact also implies that the environmental impacts generated, as a result of the production of one ton of gypsum, are significantly lower (Fort and Cerny, 2018).

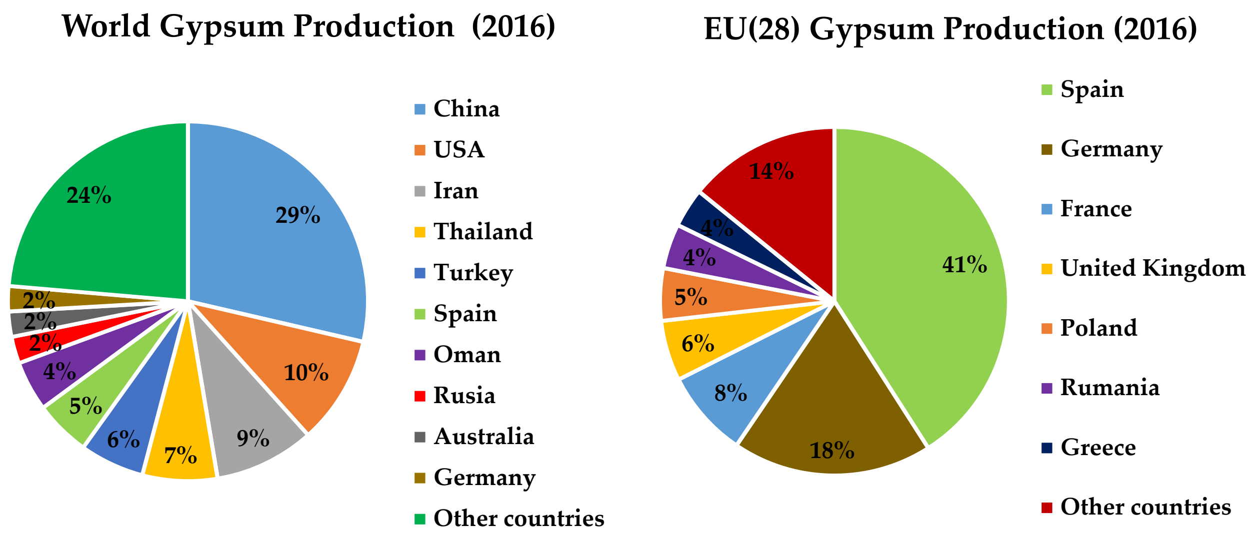


Figure 1. World and EU(28) gypsum production in 2016 (Reichl et al., 2018).

Based on the above, and among other reasons, many of the countries with fewer gypsum deposits have opted to use synthetic gypsum as a partial/total substitute of natural gypsum in the manufacture of construction products (Eurogypsum, 2019). Synthetic gypsums are materials with the same chemical composition as natural gypsum obtained from different industrial processes. One of the most common is Flue Gas Desulphurization (FGD) gypsum, which is obtained from the desulphurization of gases in coal-fired power stations (Wirsching et al., 1994).

Several researches and companies in the construction sector have found in FGD gypsum an appropriate substitute of natural one, using it in the production of plasterboards, as additive in cement mortars and concretes and for agricultural uses (Lee et al., 2012; Lei et al., 2017; Watts and Dick, 2014). In 2007, a study that analyzed the mechanical behavior and the hydrothermal properties of calcined FGD gypsum plasters were conducted by Tesarek et al. (2007). They found a highly qualified material to be used in construction, with excellent strength properties. Calcined FGD gypsum was also used by Leiva et al. (2010) to develop gypsum panels, trying to see how the fire resistance of the panel changed. As a result, they obtained an improvement in the insulation capacity of the new panels, compared to a conventional one. Later, Zhang et al. (2016) obtained an improvement in the thermal conductivity of gypsum plasters when FGD gypsum was used as a substitute for the natural one. Finally, in recent research, Fort and Černý (2018) compared the processes to obtain FGD gypsum and natural gypsum in the Czech Republic, in order to analyze the carbon footprint of both materials. They achieve a reduction of 25.2 % the CO_2 emissions for the FGD gypsum fabrication process.

Furthermore, one of the best advantages of using gypsum materials is that they can be fully recycled, as their chemical composition does not change (GtoG Project, 2015). For that season, many researchers have studied the use of recycled gypsum as a partial/total substitute of a natural one, reducing the large amounts of construction and demolition wastes that are generated each year in the world (Pacheco-Torgal, 2014). Trying to achieve the optimal development of the recycled plasters, one of the most studied variables is the calcination temperature of the recycled gypsum. In that sense, Erbs et al. (2018) studied the influence of various heating conditions, changing the temperature and the exposure time. They concluded that the best mechanical development was obtained when the material was exposed at 180 ºC for 24 hours. Previously, Rossetto et al. (2016) changed the exposure times, maintaining the heating temperature fixed at 150 ºC, using different heating times. Recently, Pedreño-Rojas et al. (2019) found that it was possible to use gypsum waste from plasterboard production as a substitute for the natural one without submitting the material to a previous calcination treatment. They achieved an improvement in terms of mechanical properties and lightness, while the workability of the plasters worsened. Imteaz et al. (2019) studied the environmental and geotechnical suitability of recycling waste materials from plasterboard manufacturing

On the other hand, not many works have analyzed the environmental impacts of using recycled gypsum. In this context, Suarez et al. (2016) studied the energy consumption and CO_2 emissions of using natural and recycled gypsum as set retarders in the production of cement mortars. They achieved a reduction of emissions and consumed energy of 65% for the recycled gypsum production process compared to the traditional one. Later, they also analyzed the influence of gypsum waste on the environmental impacts of concrete preparation (Suarez et al., 2018). The life cycle analysis of the recycling gypsum plasterboard in the EU-27 context was also studied (Jimenez-Rivero et al. 2016). Camarini et al. (2016) evaluated the energy consumption of several calcination temperatures during the production of recycled gypsum, achieving that the heating at 150 ºC had the best performance. However, most of the studies conducted to date presented the absence of primary data, as they mostly used information from databases. Some more objective factors, such as purity of the raw material, used technology, transportation, and other regional particularities (Zhang and Wang, 2016; Fort and Cerny, 2018) should be taken into account as well. Recently, other researches have analysed the recycling performance of different construction waste, taking into account several aspects such as the quality of the treatment plants (Galán et al., 2019), the search for a circular construction (Ghaffar et al., 2020) and their applications (Silva et al., 2019).

In this paper, the environmental analysis of natural and recycled gypsum production in Spain is carried out. The recycling of gypsum is based on the evaluation of the pilot program aimed at maximization of gypsum production efficiency and reduction of waste production. All the information presented was obtained from a medium-size gypsum manufacturer located in Jaen (Andalusia), one of the best regions in terms of gypsum purity (IGME, 2018). The life cycle assessment of gypsum manufacture procedures was carried out and compared with other previous studies, manufacturers' reports data and types of gypsum. Revealed results promote a partial replacement of natural gypsum by collected waste materials obtained within final product manufacturing and overall environmental benefits associated with the pilot plan is recognized. Contrary to most of the other previous researches, the information given was obtained on primary data given by the producer, and the regional factors were also taken into account.

2. MATERIALS AND METHODOLOGY

In order to calculate the environmental impact of the production of each type of gypsum, a comparative environmental analysis using the Life Cycle Assessment (LCA) methodology was conducted. In that sense, a form cradle-to-gate analysis (Klöpffer and Grahl, 2014) was developed following the instructions given by UNE-EN 14040 (2006) which means that an assessment of a partial product life cycle from resource extraction to the factory gate before it is transported to the consumer (Guinée, 2002). The environmental impact of the production of each type of gypsum was obtained as follows:

- Definition of the goal and scope of the analysis including definition of the functional unit and system boundaries.

- Identification and quantification of the different stages (and their consumptions) needed to obtain each type of gypsum. All the data were collected from the manufacturer compilation of life cycle inventories (LCI).
- Definition of the used methodology and applied life cycle impact assessment (LCIA).
- Comparison of the results of the LCA with the mechanical performance of each material. To implement this goal, two new coefficients (eq. 1 and 2) have been used, relating the results obtained for the endpoint categories analysis *E* (mPt) with the flexural *Fs* (MPa) and compressive *Cs* (MPa) strength of each plaster. The mechanical results for the plasters were just obtained for previous research (Pedreño-Rojas et al., 2019), according to the European Standard (UNE EN 13279-2, 2006).

$$F = \frac{Fs\ [\mathrm{MPa}]}{E\ [\mathrm{mPt}]} \quad (1) \qquad\qquad C = \frac{Cs\ [\mathrm{MPa}]}{E\ [\mathrm{mPt}]} \quad (2)$$

2.1. Goal and scope of LCA

The main objective of this work is to conduct the environmental assessment of the production of each type of gypsum, determining the real environmental benefits of replacing natural gypsum with a recycled one. In order to conduct the environmental analysis, from cradle to gate study was carried out.

2.2. Functional unit

The functional unit for this study was defined as 1 ton of manufactured gypsum to develop gypsum plasters with, at least, similar mechanical properties (Pedreño-Rojas et al., 2019).

2.3. System boundaries and limitations

For this study, three different scenarios were taken into account. The reference one was linked to the production of natural gypsum. Furthermore, two different types of gypsum waste were used to obtain the recycled gypsum as described below. The system boundaries, with all the phases, for each type of gypsum is presented in Figure 2.

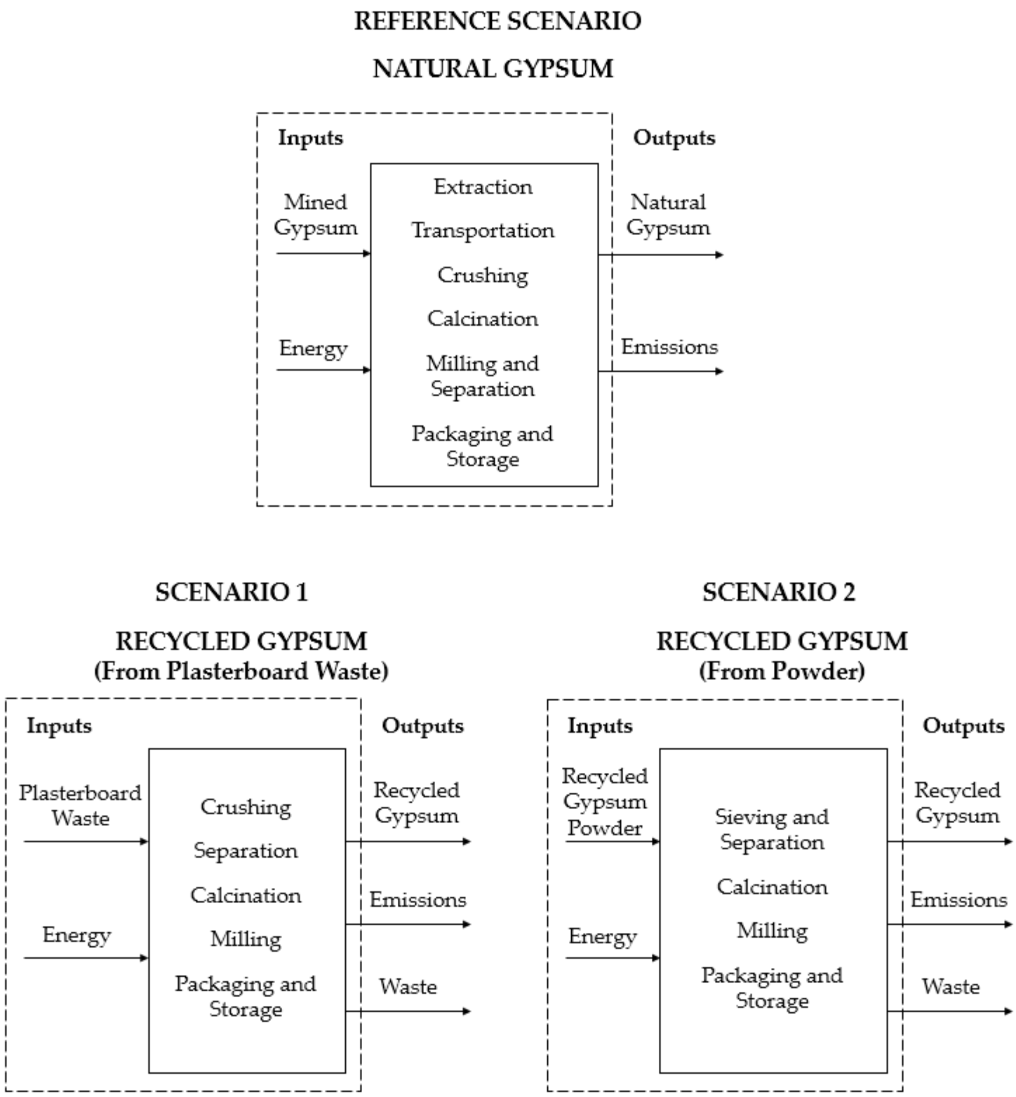


Figure 2. System boundaries for the production of each type of gypsum under analysis.

2.3.1. Reference scenario: natural gypsum

The natural gypsum producer taken as reference for this research is located in Alcaudete (Jaen, Andalusia), a region in the southeast of Spain where most of the biggest gypsum deposits in the world are located. They have been working in the gypsum production since 1969. In their factory, they carry out the complete production process, from the extraction of gypsum rock from their own quarry to its packaging, palletization and loading. Their gypsum factory presents a production capacity of 60 thousand tons per year. The exploitation takes place by staggered benches of the order of 8-10 m of height each one. The gypsum is white-alabaster and has high fineness and purity. In this quarry, the roof of the formation is made up of a dolomite layer of 2 m of power.

In order to produce the gypsum material, the following stages are carried out (Figure 3):

- **Extraction:** The calcium sulfate dihydrate is extracted from the quarry, located 11 km from the factory. Blasting is carried out on different fronts and the raw material is selected and transported by lorry to the factory. The size of the stones can be up to 50 cm in diameter.
- **Crushing:** The crushing of the stone is done with an impact mill with screens of 110 kW. The approximate granulometry obtained is shown in Table 1.

Table 1. Approximate granulometry of the gypsum after the grinding stage.

Sieve size [mm]	Retention [%]
0 – 0.3	50
0.3 – 0.5	40
0.5 – 1	10

- **Calcination:** The calcination is carried out in a rotary kiln with direct fire. Every day 300 tons of gypsum stone are calcined; a total of 60,000 tons per year, of which 20% is used to produce bagged powder products.
- **Milling and separation:** The subsequent operation is the milling to obtain gypsum, with a grinding fineness of 15-20% of retention in 0.2 mm sieve and 3-4% in 0.8 mm. In order to obtain finer gypsum, the material is derived to the separators, obtaining values of fineness of grind <1% of retention, in 0.2 mm sieve.
- **Mixing:** For the manufacture of special gypsums, the mixing plant is used where the gypsum is added with setting retarders, thickeners, water retainers, fluidizers and various aggregates. None of these additives are taken into account for this research.
- **Packaging and storage**.
- **Distribution**.

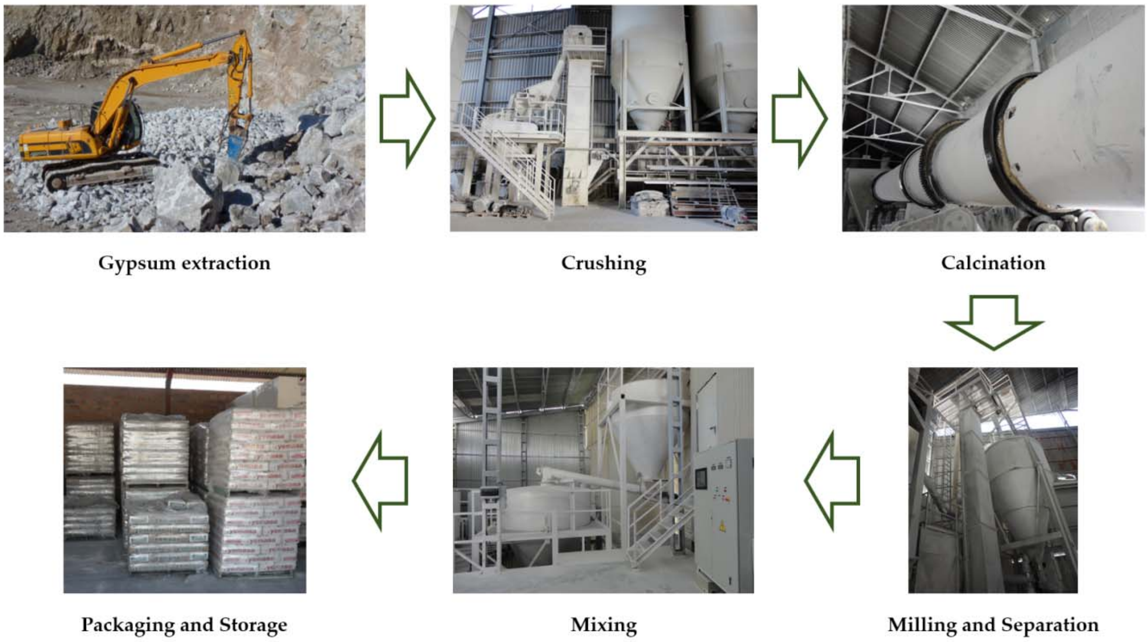


Figure 3. Stages in the production of natural gypsum.

2.3.2. Scenario 1: recycled gypsum from plasterboard waste

It was obtained from the production waste generated in the manufacture of the gypsum panels in the plant (Figure 4A) and usually remain discarded. As part of a pilot program aimed at increasing production efficiency and waste reduction, it was collected in large pieces (up to 15 cm), which included the board of the panels. Such collected waste must be subjected to a process of grinding and subsequent separation, with the aim of separating the gypsum material from the rest of impurities. After that, the material was submitted to calcination, milling and packaging phases (Figure 2), in a procedure with the same characteristics as the natural gypsum one. The only difference, regarding the machinery used, is found in the calcination process. In this case a natural gas furnace (13.59 m^3/ton) was used instead of a rotary kiln. Furthermore, it should be noted that the transport of the material to the factory was ignored, as it was generated inside the production plant and no further transportation is needed.

2.3.3. Scenario 2: recycled gypsum from gypsum powder waste

It was obtained from the powder generated during the plasterboards' cutting process of the plasterboard manufacturing plant (Figure 4B). In the frame of the pilot program, this material is further processed to decrease the amount of produced waste. As it comes as a powder, to be used as recycled gypsum it was only submitted to calcination, milling and separation stages, avoiding the grinding phase (Figure 2). As for the previous scenario, the transport of the material to the factory was also ignored because material is generated at the same location.

The mineralogical composition of both recycled gypsum (in their original stage) was identified using XRD and, contrary to expectations, a predominance of hemihydrate particles (bassanite) versus dihydrate ones (gypsum) was observed (Pedreño-Rojas et al., 2019).

A. B.

Figure 4. Recycled gypsums in their original state. A. Plasterboard waste. B. Recycled gypsum from plasterboard waste.

3. LIFE CYCLE INVENTORY (LCI)

All the presented data collected to develop the study were directly taken from the manufacturer, trying to obtain a real analysis of the environmental impact of the whole production processes. All the individual manufacturing phases were taken into account. The quarries were located 11 km from the production plant, using 25-ton diesel lorries for the transport. In the case of the recycled gypsum, the collection and transport to the factory have not been taken into account, as they are waste generated in the production plant. The transport of the packaged material was neglected in this study since it is only intended to know the environmental impacts of the production process. The diesel fuel consumption of the machinery used (tractors, lorries, etc.) was estimated using the consumption records of the company. Finally, the electricity consumption of the machines was obtained checking the machine producers information with the real data of consumption.

All the information about the phases and their consumptions are presented in Table 2.

Table 2. Life cycle inventory of gypsum production.

Phase description	Energy consumption per ton of gypsum	Fuel type
REFERENCE SCENARIO: NATURAL GYPSUM		
Gypsum extraction	5.56 l	Diesel
Transport to the manufacturing plant	0.16 l	Diesel
Crushing using an impact mill	32.61 kWh	Electricity
Calcination in a rotary kiln	29.59 m^3	Natural gas

Milling and separation	14.85 kWh	Electricity
Packaging and storage	11.23 kWh	Electricity
Internal transport	7.14 kWh	Electricity
SCENARIO 1: RECYCLED GYPSUM (PLASTERBOARD WASTE)		
Crushing using an impact mill	32.61 kWh	Electricity
Separation	0.9 l	Diesel
Calcination in a furnace	13.59 m^3	Natural gas
Milling	10.48 kWh	Electricity
Packaging and storage	11.23 kWh	Electricity
Internal transport	6.03 kWh	Electricity
SCENARIO 2: RECYCLED GYPSUM (POWDER)		
Sieving and separation	0.9 l	Diesel
Calcination in a furnace	13.59 m^3	Natural gas
Milling	10.48 kWh	Electricity
Packaging and storage	11.23 kWh	Electricity
Internal transport	4.26 kWh	Electricity

4. LIFE CYCLE IMPACT ASSESSMENT (LCIA)

To develop the LCIA, the authors decided to use the IMPACT 2002+ methodology (Joillet et al., 2003; Yañez, 2008), as it was also followed by other researchers to evaluate the LCA of building materials (Suarez et al., 2016). With that methodology, the following midpoint impact indicators were measured: carcinogenic and non-carcinogenic effects, photochemical ozone formation with respiratory organic effects, abiotic depletion due to mineral extraction, global warming, ozone depletion, acidification, eutrophication, land occupation, non-renewable energy, and respiratory inorganics. Furthermore, human health, ecosystem quality, climate change and resource endpoint impact indicators were also determined.

All the data collected to develop the study were directly taken from the manufacturer, using SW – Simapro 8.5 software to organize the inventory data and to perform the impact assessment. Ecoinvent database 3.3 was also used.

5. RESULTS

5.1. MidPoint indicators

The results obtained for the midpoint indicators for each type of gypsum are shown in Figure 5. It can be observed that in all impact indicators except mineral extraction, natural gypsum generated a greater impact compared to recycled gypsum options. This difference reached its highest value in the category of ionizing radiation, where there was an 87.82% increase with respect to gypsum from plasterboard waste. In addition, it is important to point out that recycled gypsum powder is the one that generates the least impact in all the categories analyzed, reaching 67.57% lower than that coming from plasterboard. Considering the global warming potential of particular gypsum types production, gypsum recycling can deliver about 40 to 45% savings when compared to natural gypsum manufacturing. This fact refers to the overall benefits of waste material recycling for reaching the ambitious carbon restriction goals accepted by the EU (Newbery, 2016). Another significant positive side-effect of gypsum recycling can be seen in the lowered energy consumption for the fabrication of recycled gypsum. Here, a decrease of almost 60 % was noted which complies with efforts leading to reduced energy consumption demands of the construction sector.

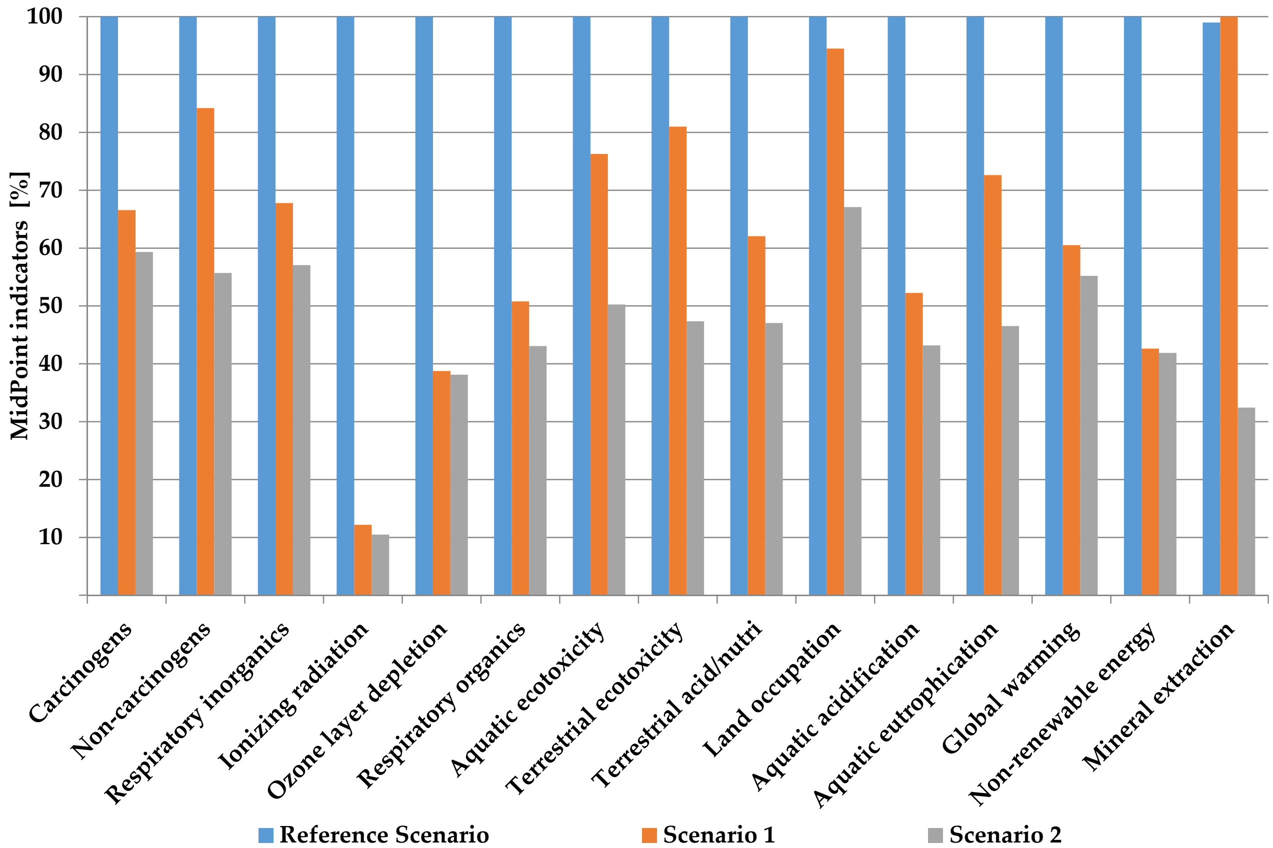


Figure 5. MidPoint indicators results. Comparison between each type of gypsum under analysis.

Analyzing in detail the results obtained for each of the materials, Figure 6 shows the impacts generated by each of the phases or stages in the generation of natural gypsum. In view of the results, it can be seen how the influence of each of the phases varies substantially according to the impact category analyzed. In this sense, the gypsum extraction phase reached its greatest relevance for the ionizing radiation (84.38%) and aquatic eutrophication (43.93%) categories. For its part, the crushing and grinding process were predominant in the impact indicators of terrestrial ecotoxicity (33.76%) and mineral extraction (44.88%). In the rest of the impact indicators, a predominance of the calcination phase was observed, especially when focused on global warming or non-renewable energy demand. Finally, it is important to highlight that the packaging and storage phase (common to all the gypsums understudy) was the one that generated the least impact in most of the analyzed categories.

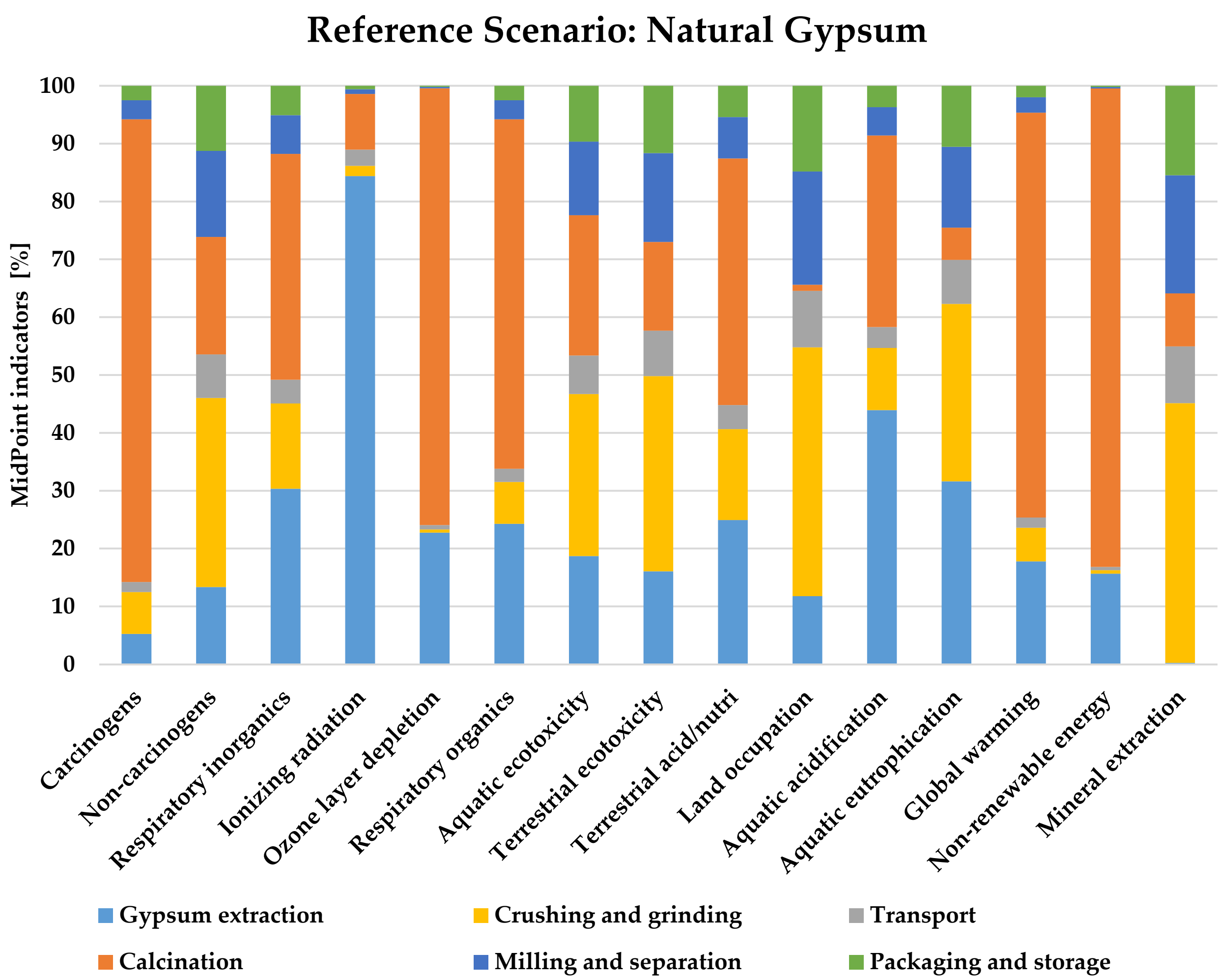


Figure 6. MidPoint indicators results for natural gypsum production phases.

On the other hand, the results obtained for each phase in the generation of recycled gypsum from plasterboard waste are presented in Figure 7. In this case, there was a much more significant variation depending on the impact category analyzed. In this sense, the crushing and grinding phase predominated in six in the categories analyzed, the milling and separation phase in ionizing radiation, while in the rest of the categories the calcination phase stood out significantly. In addition, unlike for natural gypsum, since the transport of the material to the factory has been eliminated, as it was generated there, the transport phase was the one that, in general, achieved the least impact.

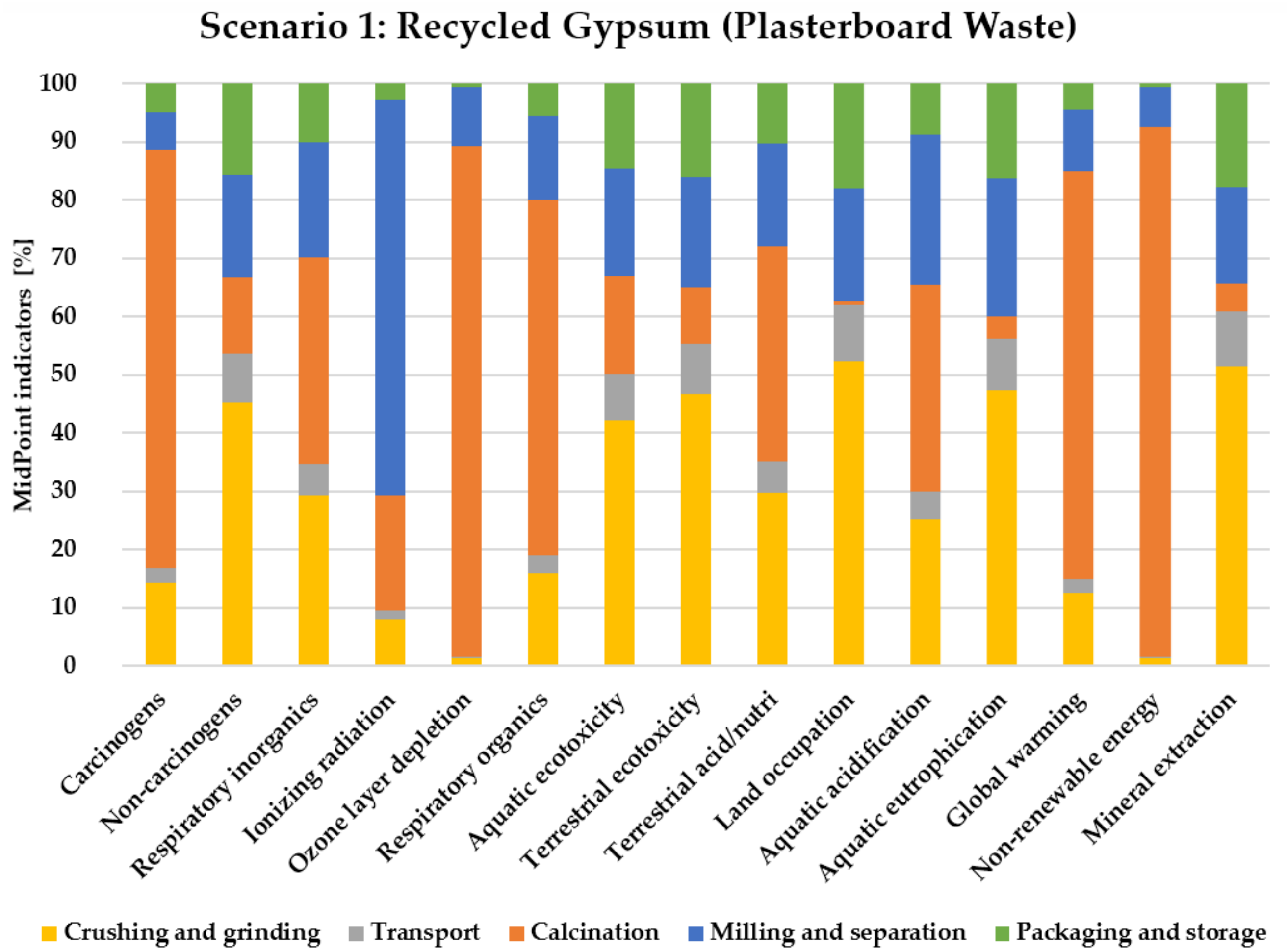


Figure 7. MidPoint indicators results for recycled gypsum (plasterboard waste) production phases.

Finally, analyzing the results obtained for recycled gypsum (powder), a predominance of the calcination phase can be seen in most of the impact categories studied (Figure 8), reaching, for example, 82.12% of the total impacts of global warming. The milling and separation phase predominated in four of the categories, while the packaging and storage phase was most distinct in the mineral extraction.

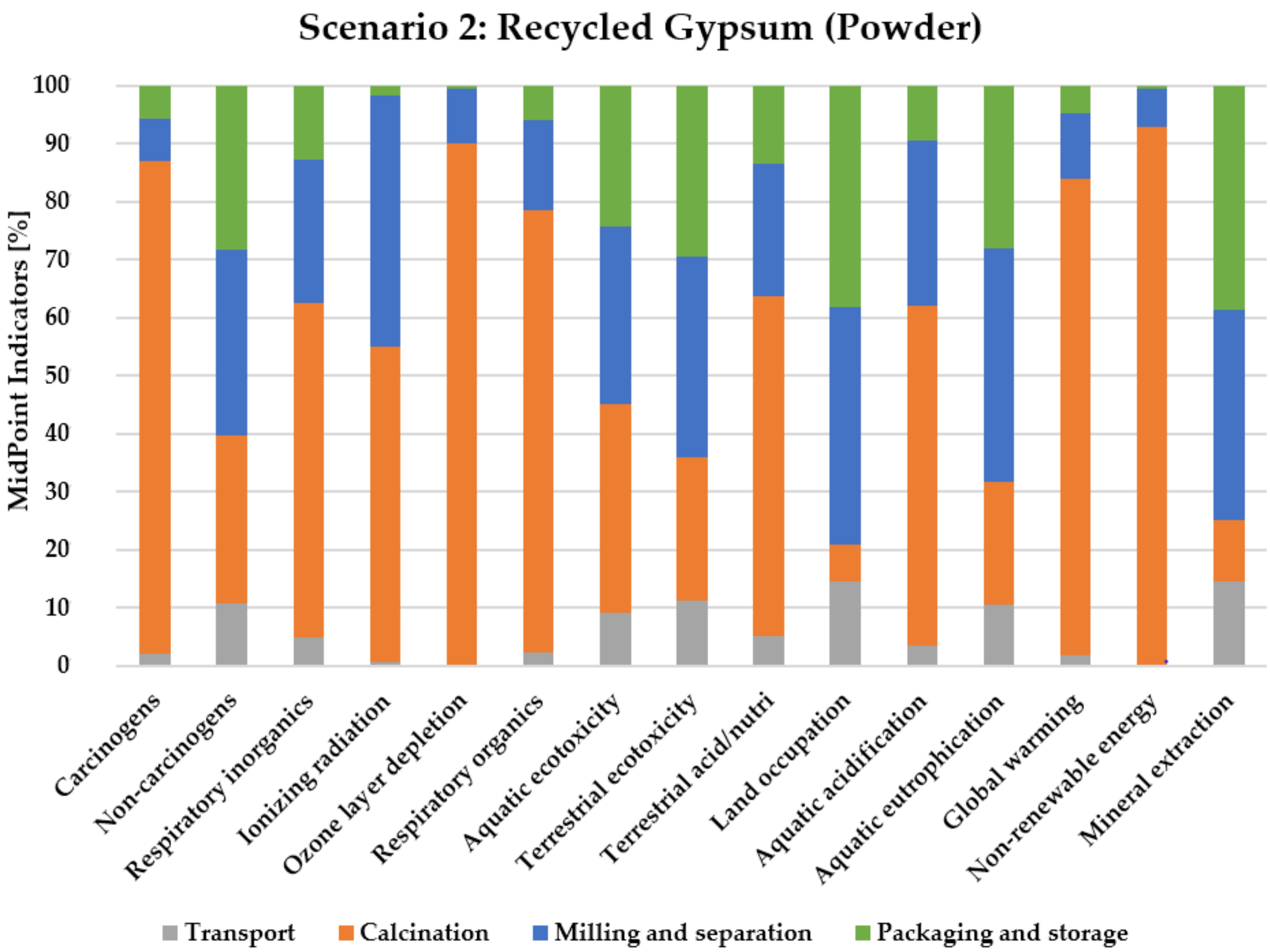


Figure 8. MidPoint indicators results for recycled gypsum (powder) production phases.

5.2. EndPoint indicators

The results obtained for the normalized endpoint indicators are presented in Figure 9. As can be appreciated, an important reduction of the environmental impacts was achieved when recycled gypsum production was compared with the natural one. In that sense, the biggest reduction was obtained for the resources category (56 and 58 %), on which all the materials achieved their highest impact. In general terms, the best results, as for the midpoint categories, were obtained for the recycled gypsum (in powder) production, being its results similar to that achieved for the one from plasterboard waste (only 6% lower).

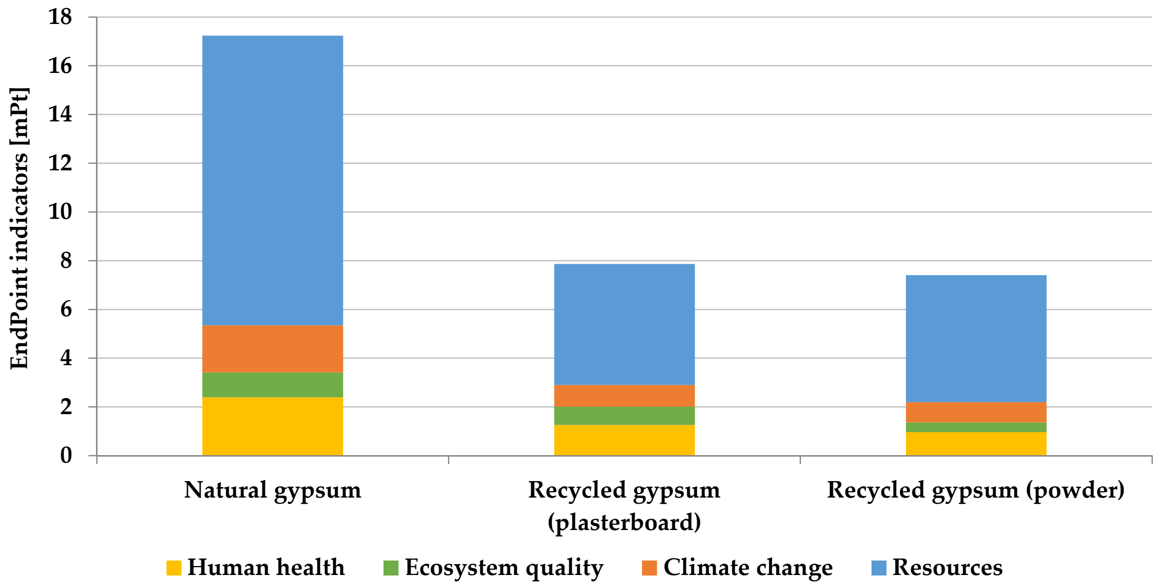


Figure 9. EndPoint indicators results. Comparison between each type of gypsum under analysis.

5.3. Combined assessment of mechanical and environmental properties

In order to compare the results of the LCA with the mechanical performance of each material, two new coefficients (eq. 1 and 2) have been used, relating the results obtained for the endpoint categories analysis with the flexural (F) and compressive (C) strength of each plaster (Table 3).

Table 3. Combined assessment of mechanical and environmental properties.

Scenario	F [MPa/ mPt]	C [MPa/ mPt]
Reference Scenario: Natural Gypsum	0.18	0.43
Scenario 1: Recycled Gypsum (Plasterboard)	0.28	0.81
Scenario 2: Recycled Gypsum (Powder)	0.31	0.97

The results for the combined assessment show an important improvement for both types of recycled gypsum, being slightly better the values achieved for the gypsum waste in powder for both coefficients. On the one hand, in comparison with flexural strength values, an improvement of 35.7% was achieved for Scenario 1 and 41.9% for Scenario 2. On the other hand, for the compressive strength combined assessment, the benefits were 46.9% for Scenario 1 and 55.7% for the recycled gypsum in powder, compared to the reference scenario. Thus, for both coefficients, Scenario 2 was the one that showed the best environmental performance including mechanical properties.

6. DISCUSSION

The data obtained for the LCA of the different gypsums studied can be compared with other studies in the literature that have also analyzed the environmental impacts generated by gypsum production. In that sense, Suarez et al. (2016) also used the IMPACT 2002+ methodology to study and compare the LCA of natural and recycled gypsum production. Our results are in accordance with their conclusions, as the main environmental impacts for both types of gypsum were obtained for the calcination phase using natural gas.

Furthermore, the global warming potential results for natural gypsum can also be compared with the study conducted by Fořt and Cerny (2018) when they obtained the carbon footprint of natural and FGD gypsum in the Czech Republic. In both studies the results were taken directly from the production plant and, despite the fact that the trend between the two results is very similar, it was observed that in the Spanish company there was an improvement in the impacts obtained for natural gypsum (Figure 10). This fact can be easily explained, as Spain is one of the world's largest producers of natural gypsum, which means that the quantities produced by the companies in the sector are substantially higher each year than in other countries such as the Czech Republic. Thus, as the volume of production is higher, the environmental impacts generated per ton of gypsum will be lower.

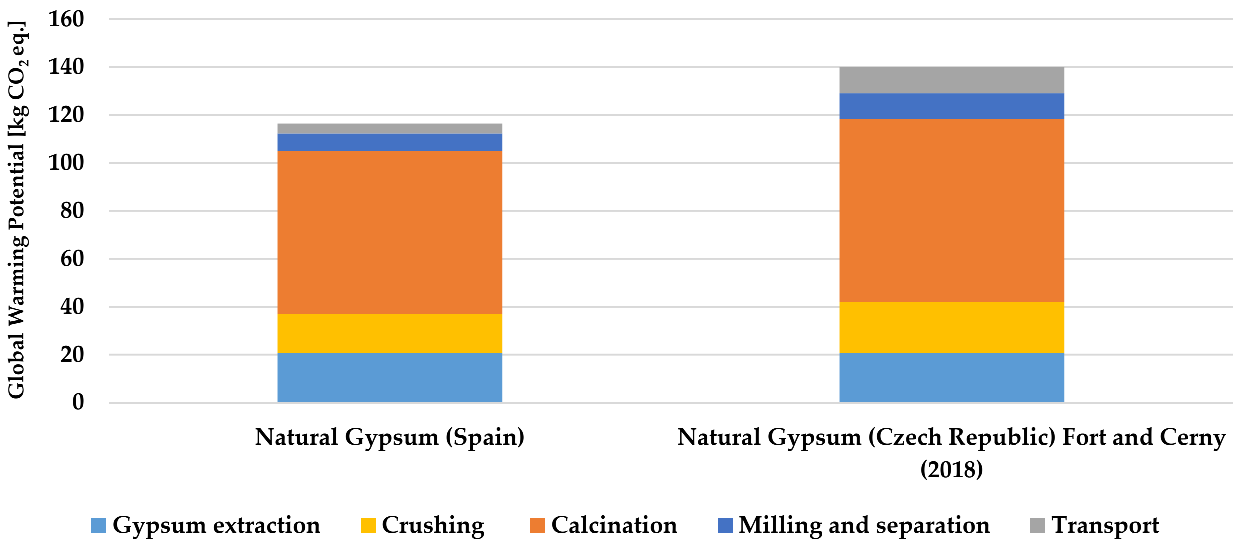


Figure 10. Global warming potential for natural gypsum production. Comparison between the Spanish and Czech analysis.

Apart from natural gypsum, they obtained the carbon footprint of FGD gypsum, as the most widespread alternative to natural gypsum. They achieved a substantial improvement in FGD impacts with respect to natural gypsum. However, it is necessary to propose new alternatives to FGD gypsum and encourage the use of recycled plaster. As already mentioned, this type of synthetic material is generated as a result of the desulfurization of gases in thermal power plants, which, according to the various regulations and environmental commitments (Wynn and Coghe, 2017; Rogelj et al., 2016), are doomed to disappear in close future (Dolter and Rivers, 2018; Figueiredo et al., 2019).

In addition, using a recycled material that usually ends in landfills (which would be decomposed as hydrogen sulphide H_2S (Yang et al., 2006)), we are promoting many other crucial aspects for the building industry, such as recycling, utilization of waste materials towards a circular economy (Pacheco-Torgal, 2014). In that sense, some studies indicate that prolonged exposure to low H_2S concentrations may pose adverse health effects on susceptible populations and to the environment (Campagna et al., 2004). Moreover, if demolition works will be precisely planned and coordinated together with the production of new gypsum products, a current building stock can be viewed as a resource bank that can be effectively utilized especially in countries with limited or completely abandoned landfill sites. The reuse of waste materials represents a substantial step toward the preservation of natural resources and mitigation of negative externalities associated with industrial production.

Linking the LCA results for gypsum recycling with similar studies from the literature, it can be seen that, in our case, a significant reduction of the impacts associated with recycled gypsum, compared with those researches, was achieved (Suarez et al., 2016; Jiménez-Rivero et al., 2016). This fact can be explained by the suppression of waste transport to the treatment plant phase. Transportation distances have a negative effect on eco-efficiency. Consequently, recycling is often limited due to the high impact of transportation (Simion et al., 2013; Chen et al., 2019). The study conducted by Suarez et al. (2016) analyzed the influence of the transport phase on the environmental impact of recycled plaster. To do this, they proposed three different scenarios in which they changed the distance from the waste collection point to the manufacturing plant (7, 30 and 50 km). It was observed that a greater environmental impact than natural gypsum in the categories of eutrophication and non-carcinogenic effects were obtained for the scenario with 50 km distance, which complies with the investigation of Zhang et al. (2019), who have described the effects associated with a construction and demolition waste pre-sorting and transportation. Comprehensiveness, including not only waste reuse, but particularly optimization of resources management by the meaning of closed loops is deemed as more efficient in an environmental point of view as concluded by Hossain and Ng (2019). In that sense, the reuse of various gypsum waste produced in the same manufacturing plant involves the elimination of the transport phase and all the impacts that it entails, thus achieving a more effective way to reuse the gypsum residue and reduction of waste production. It is a partial step to obtain an efficient and fully circular economy model. On the other hand, obtaining waste from demolition works or landfills means that, subsequently, such residues must be subjected to a selective selection process, which implies an additional environmental impact, damaging the efficiency of recycling, since buildings are demolished selectively only rarely (Di Maria et al., 2018).

Finally, it is essential to point out that if the calcination phase were suppressed in the generation of recycled gypsum (powder), which is viable according to the tests carried out by Pedreño-Rojas et al. (2019), the environmental impacts of this material would be substantially reduced, standing, on average, between 25 and 30% of those reached for natural gypsum. This fact clearly points to the necessity for the complex assessment of building materials including both functional and environmental properties in order to provide the most optimal solution from a broader perspective. Moreover, the single score preference prevents the advancement towards sustainable development, especially in the case of the construction industry which struggles with environmentally-related issues.

5. CONCLUSIONS

This article promotes the development of gypsum plasters made with fully recycled materials, achieving an important reduction in carbon emissions during its manufacturing procedure. This fact is in accordance with the target set by the European Union, which seeks to achieve a long-term carbon-neutral economy (Newbery, 2016; Dominković et al., 2016). One of the proposed steps to achieve this goal is to reduce the greenhouse gas emissions of member countries by more than 60% in 2050 (Mikova et al., 2019), helping this proposal to achieve that objective. The main objective of this research was to reduce the environmental impacts of gypsum production in Spain by using various waste generated in the production processes. To conduct the analysis, the Impact 2002+ LCA methodology was used. In our work, the LCA was performed on the basis of primary data given directly by the producer, and the regional factors were also taken into account. This article promotes the employment of advanced resources management in the gypsum production industry including waste reduction thanks to the reuse of discarded material from various production stages. According to the results achieved, the following conclusions can be drawn:

- Utilization of residues from gypsum products manufacturing is beneficial from the environmental point of view despite the contamination by other materials. Comparing the production stages of natural gypsum with recycled ones, it could be observed how, in the case of recycled gypsums, some phases, such as calcination or even crushing in some circumstances (Scenario 2), are suppressed.
- The results obtained for the endpoint indicators showed an important reduction of the environmental impacts when recycled gypsum production was compared with the natural one. In that sense, the biggest reduction was obtained for the resources category (56 and 58 %), on which all the materials achieved their highest impact.
- The efficient utilization of waste and raw material streams can substantially reduce the negative environmental impacts associated with gypsum production. Moreover, pilot projects aimed at maximal reuse of waste materials without any transportation distances from demolition sites can improve overall productivity to facilitate a transition to the circular economy model including the recycling of gypsum transported from construction sites.
- When comparing the obtained results merging both functional and environmental properties of studied materials, a significant benefit can be assigned to the recycled gypsum products. The gypsum recycling provided the same or even better mechanical properties (Pedreño-Rojas et al., 2019) accompanied by decreased environmental impact (around 40%) and thus better environmental efficiency. It could be noticed that Scenario 2 (recycled gypsum in powder) was the one that showed the best environmental performance including mechanical properties.
- Performed environmental analysis reveals that the employment of similar pilot projects can contribute to matching carbon-neutral economy goals set by the European Union. In that sense, a reduction of the CO_2 emissions by more than 60% must be achieved in 2050, contributing to the new plasters to achieve that target. Furthermore, it was proved that the GWP results of the recycled scenarios are lower than those obtained for the production of other alternatives like FGD gypsum.
- Performing the endpoint LCA analysis, the obtained results can be easily compared and coupled with various functional parameters as showed in this paper despite the higher level of uncertainty. Notwithstanding, recycling of building materials needs to be linked with the preservation of material properties to avoid downcycling.

- Finally, in order to provide new research lines, natural gypsum production in many other countries can be studied following the same methodology. The differences between big producers (China or Iran) and small ones (Czech Republic) should be noticed. On the other hand, alternative recycled gypsum scenarios (construction and demolition waste, etc.) can also be evaluated.

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