minerals

Article

Environmental Evaluation of Gypsum Plasterboard Recycling

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Abstract: Gypsum is widely used in the construction sector, and its worldwide consumption has been increasing for several decades. Depending on the lifetime of the used gypsum products, an increase of gypsum in construction and demolition waste follows. Especially against the background of a circular economy, the recycling of waste gypsum is of growing importance. However, the use of recycled gypsum only makes sense if it is environmentally friendly. Therefore, an evaluation of the environmental impacts of industrial-scale processing for the recycling of post-consumer gypsum waste was conducted. The evaluation was performed with an established life cycle assessment software. Original data provided by the industry and complementary data from a database for life cycle assessments were used for the calculations. Two scenarios for recycled gypsum with different transportation distances were calculated. These results were compared with the results of the environmental evaluation of gypsum derived from coal-fired power plants (FGD gypsum) and natural gypsum. The results showed that the utilization of recycled gypsum can be environmentally advantageous compared to the use of natural gypsum or FGD gypsum, especially in the impact categories of land transformation and resource consumption (abiotic depletion potential). For most environmental impact categories, the specific transportation distances have a strong influence.

Keywords: gypsum plasterboards; gypsum waste; recycled gypsum; environmental evaluation; LCA

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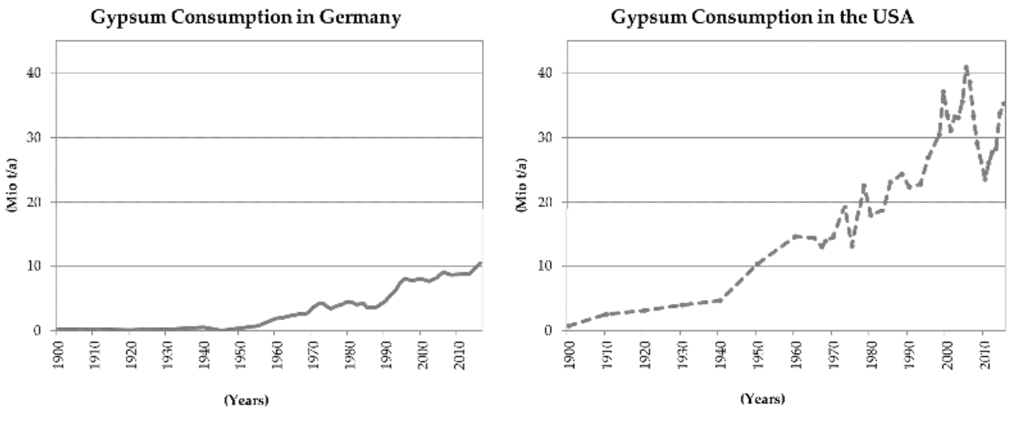
1. Introduction

The use of secondary building materials can meet the requirements of sustainability in several ways: the extended time availability of primary raw materials and, thereby, the protection of natural resources, as well as the conservation of landfill sites. Depending on the respective circumstances, other environmental impacts like the emission of greenhouse gases could also be reduced [1]. Due to the large quantities of required raw materials and, also, the high volumes of construction and demolition waste (CDW), the reuse of waste from the building sector is of high importance for the reduction of waste masses in general and, also, for a circular economy [2,3]. Accordingly, many studies have been conducted to perform life cycle assessments (LCA) for several aspects of the building material cycles [2,4].

There are already established procedures to recycle and reuse mineral waste materials in civil construction. Due to the large amounts and the material properties of concrete and concrete waste, several studies have been performed to use crushed concrete as environmentally friendly recycled concrete aggregates (RCA) [5]. These recycling procedures are already applied in practice [1]. Furthermore, various approaches have been made to find new procedures and applications for the reuse of different CDW components. Colman et al. investigated the use of the sand fraction from the CDW pieces as an additive in mortar production [6]. Due to material properties like elevated water absorption or contaminations, this sand fraction can usually not be used as an RCA. The authors found the material suitable for mortars and determined that even the gypsum residues in this fraction did not affect the mechanical properties of the new mortars.

In a study from Azevedo et al., solid waste from the red ceramic industry was used for geopolymer synthesis [7]. It was found that this waste has a great potential to be used as the raw material for obtaining ceramic roof tiles by means of geopolymeric reactions. Amaral et al. worked on a methodology for the partial replacement of natural sand in mortars by ornamental stone-processing waste [8]. They used a mathematical model for the calculation of an optimal particle size contribution. The results indicated a possibility to produce eco-friendly mortars from that waste. Marvila et al. developed a mixture of gypsum plaster and rock waste for the repairs of historical buildings [9]. This investigation showed promising results in renderings to repair the studied buildings, namely when 25% of the sand was replaced by rock waste.

In recent years, gypsum as a building material has attracted attention. It has been widely used in constructions in the last decades, and its consumption has increased in many countries. Figure 1 shows the development of the gypsum consumption in Germany and the U.S. since 1900. These numbers include gypsum that arises as side product from coal-fired power plants (FGD gypsum). Between 2000 and 2019, the quantity of FGD gypsum was about seven million tons each year in Germany [10]. In 2019, the contained quantity of FGD gypsum in the U.S. was 22.9 million tons [11]. The estimated global production of gypsum in 2019 was 140 million tons [12]. Accordingly, a rise of gypsum waste (GW) in CDW is expected in the upcoming years, and the importance of gypsum recycling is a growing issue [13,14]. Currently, the gypsum demand is covered (at least 60%) by FGD gypsum in Germany. The natural gypsum deposits fulfil the remaining gypsum demand [10]. Due to the national climate protection goals and the related shutdown of coal-fired power plants, the FGD gypsum supply will decrease significantly in the future. Additionally, the available extraction areas will not be approved due to nature conservation reasons. Therefore, the recycling of gypsum waste is a contribution to solving future gypsum demand problems.



(**a**) (**b**)

Figure 1. Gypsum consumption in Germany (**a**) and the USA (**b**) in Mt/a [15–17].

Gypsum is suitable for closed-loop recycling due to its chemical composition. It consists mainly of calcium sulfate in the form of three crystalline phases with varying hydration levels: calcium dihydrate, $CaSO_4{\cdot}2H_2O$ (calcium sulfate dihydrate, typically called gypsum), $CaSO_4$ (anhydrite), and calcium sulfate hemihydrate, $CaSO_4{\cdot}0.5H_2O$ (bassanite). While gypsum and anhydrite are naturally occurring minerals, calcium sulfate hemihydrate can be produced by dehydration in the thermal treatment of gypsum at a temperature range between 125 °C and 180 °C (Equation (1)). This reaction, called calcination, is reversible and, in contact with water calcium sulfate hemihydrate, is again transformed into calcium sulfate dihydrate in an exothermal reaction (Equation (2)) [14,18].

$$CaSO_4{\cdot}2H_2O \xrightarrow{125^{\circ}C-180^{\circ}C} CaSO_4{\cdot}0.5H_2O + 1.5H_2O \quad (1)$$

$$CaSO_4{\cdot}0.5H_2O + 1.5H_2O \xrightarrow{\text{Hydration}} CaSO_4{\cdot}2H_2O + \text{Energy} \quad (2)$$

Hemihydrate and anhydrite can be found in various crystalline structures or modifications. These modifications have differing material characteristics that allow various technical applications, according to their particular material properties [19,20]. Most of the gypsum products are used in the construction industry. While gypsum can be applied in cement production to adjust the setting time, its main application area is usage for interior fittings in buildings. Besides its utilization in plaster, decorative elements, or screeds, a large proportion of gypsum is installed in the form of drywalls, wallboards, and, especially, gypsum plasterboards [14,21]. In many countries, gypsum plasterboards are of particular importance, because they make up the highest amount of used gypsum in buildings [3,22]. Approximately 734,000 tons of gypsum plasterboard waste was generated in the year 2015 in Northern Europe alone [23].

The reversibility of the hydration and dehydration of calcium sulfate dihydrate (see Equations (1) and (2)) is comparably easy to proceed. This is essential for the recycling of gypsum waste. In general, the recycling of GW can be divided into two main stages: the collecting and preparation of GW and the calcination. An important factor for the usability of recycled gypsum is also the quality, especially the purity of the GW [24,25]. The separation of the GW from the rest of the CDW is also appropriate for another reason: sulfates are unwanted in other secondary building materials (particularly in recycled concrete aggregates) and should be minimized in these waste materials for quality reasons as well [26,27]. Therefore, the demolition, the selective dismantling, has to be carried out carefully [28].

In this context, the recycling of gypsum plasterboard waste (GPW) is advantageous, because plasterboards are comparatively easy to dismantle and to collect separately so that impurities can be minimized or almost completely avoided [14,21,28]. Gypsum plasterboards consist of gypsum embedded between cardboards. In the recycling process, these two materials have to be separated.

Accordingly, a number of studies have been conducted to investigate the recycling of GW and GPW in the last several years. Many investigations focused on the calcination process. Different temperatures and holding times and, also, the material properties of the recycled gypsum were investigated. Ahmed et al. produced a recycled gypsum plaster from GW at a temperature range of 130–160 °C [29]. A paper from Brazil described the building material properties of recycled gypsum plaster waste after calcination at ~150 °C [30]. Camarini et al. tested recycled gypsum after calcination at temperatures between 120 °C and 200 °C [13]. The building material properties of the recycled gypsum in these investigations were of good quality. Camarini et al. also determined the energy consumption and found the process environmentally advantageous. The properties of recycled gypsum from gypsum plasterboards after up to five recycling cycles were investigated by Erbs et al. [3,22]. The tests showed that the reversibility of gypsum hydration enabled the generation of recycled gypsum in three cycles without losses in the building material properties.

The environmental impacts of gypsum recycling have also been investigated. Pantini et al. investigated strategies for the recycling of GW in a specific region in Italy [31]. The authors evaluated the environmental impacts of gypsum recycling in four scenarios on a theoretical basis. The study found out that the transporting distances have a significant influence on environmental impacts in the investigated system. A study about the recycling of gypsum plasterboards in Sweden also concluded the importance of the sorting accuracy and an optimization of the transporting distances for the support of gypsum recycling [32].

Pedreno-Rojas et al. compared the environmental impacts of the natural gypsum production and the production of recycled gypsum from pre-consumer gypsum waste in Spain. The LCA evaluated the processing for natural and recycled gypsum, including calcination, but without transport. The results showed significantly lower environmental impacts from the production of recycled gypsum [33]. Another LCA in Spain, conducted by Suarez et al., also compared recycled and natural gypsum. In this investigation, the results for recycled gypsum were also lower in all impact categories. However, the low transport distances (seven km) influenced these results [34].

This paper focusses on recycling GPW and the environmental impacts resulting from the related handling and processing in Germany. The recycling process was evaluated on the industrial scale, and the assessment included real transportation distances as well [21]. This evaluation filled the gap between gypsum recycling on a lab scale and the validation of the transportation and gypsum recycling under real conditions. Furthermore, the results were derived from the recycling of post-consumer GPW and with regards to recycled gypsum that meets the comparably high-quality standards for gypsum that are required from the German gypsum industry [24,25,35].

2. Materials and Methods

This environmental evaluation was performed to calculate the ecological effects of the production of recycled gypsum from post-consumer gypsum plasterboard waste on an industrial scale. The evaluation included a comparison with data from the extraction of natural gypsum and the use of FGD gypsum. To clarify the influence of transportation for the evaluation of the production of recycled gypsum, two calculations with different transportation distances were conducted. Accordingly, four model scenarios were designed.

The environmental evaluation was based on the international standard for life cycle assessments ISO 14040/44 [36,37]. The calculation of material flows and energy consumption was carried out with Umberto (Umberto NXT universal, IFU Institut fuer Umwelttechnik, Hamburg, Germany), a software for life cycle assessments [38].

2.1. Investigated Recycling Process

The processing of the gypsum plaster waste was carried out in the stationary gypsum recycling plant of a medium-sized company. The objective of the processing is the removal of impurities, as well as the separation of gypsum from cardboard and paper. A simplified flowchart of the recycling process is shown in Figure 2.

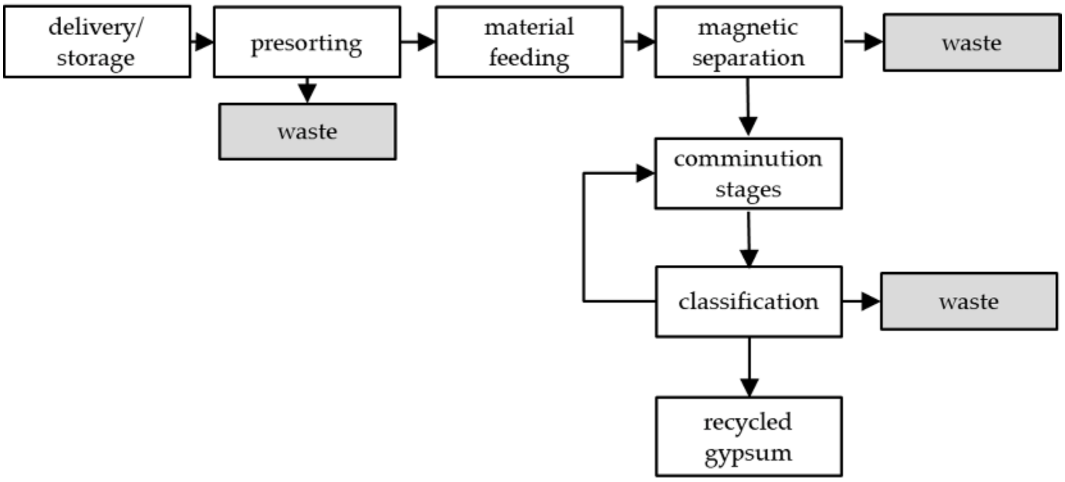


Figure 2. Simplified flowchart for gypsum recycling in a stationary gypsum recycling plant.

After presorting with an excavator and/or manually, the gypsum waste is fed into the system. In the first sorting step, ferrous metals are removed by a magnetic separator, followed by various comminution stages. During the comminution, predominantly shear forces are used to separate the gypsum from the cardboard and paper. Due to the limit for TOC (total organic carbon) in recycled gypsum, the removal of paper fibers is of particular importance. Furthermore, different grain sizes can be generated and separated in the subsequent classification stage.

It is of fundamental importance for the environmental evaluation of a processing to take all wastes or residues into account. The proportions of the waste fractions in gypsum recycling depend on the acceptance criteria of the operating company and, accordingly, the quality of the input material. Therefore, large differences in the amount of waste materials after processing are possible. In the present case, the input material (predominantly used gypsum plasterboards from construction sites) usually originated from the selective dismantling of buildings. Accordingly, only a few unsuitable materials had to be removed. Depending on the specific input material, about 2% to 3% of the material occurred as waste after presorting and magnetic separation. The removed paper and cardboard waste amounted between 10% and 17% of the input material. Correspondingly, the output of recycled gypsum ranged from 80% to 88%.

2.2. Settings for the Environmental Evaluation

The scope of this research was to investigate the environmental impacts of the production of RC-gypsum in comparison with natural gypsum and FGD gypsum. Therefore, the functional unit was 1-t gypsum.

The system boundaries were fixed with regards to the comparability of the examined gypsum types. For recycled gypsum from gypsum plasterboard waste, they included the following steps (see also Figure 3):

- the transportation of GPW (from construction sites or collection points) to the recycling plant,
- the recycling process,
- transportation to the gypsum plant,
- drying process, and
- transportation to the costumer.

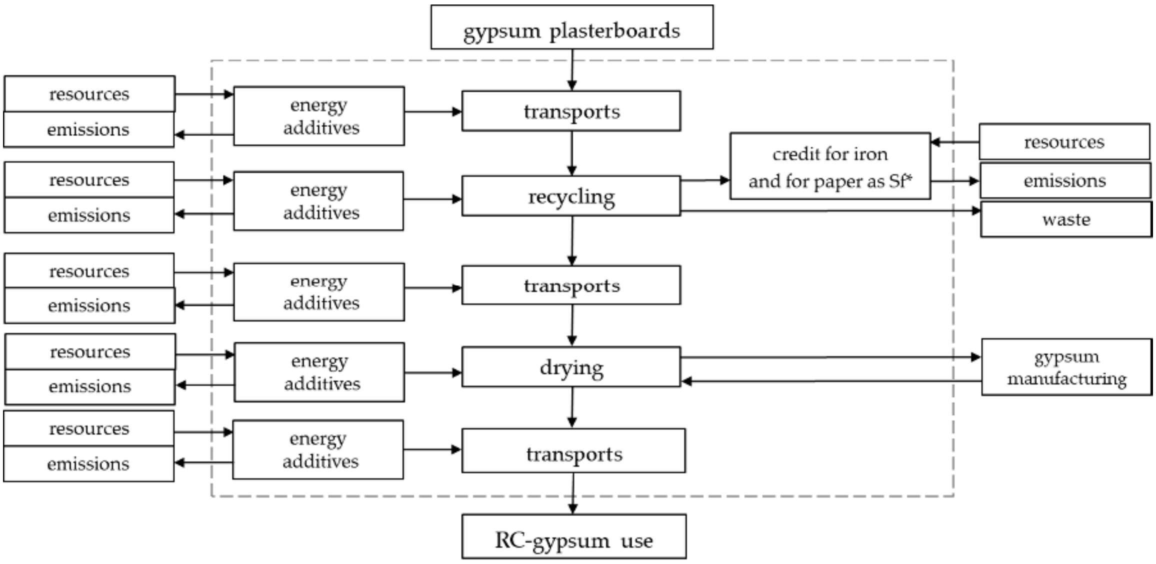


Figure 3. System boundaries for the evaluation of RC-gypsum. Sf*: Substitute fuel.

Recycled gypsum usually has a moisture content of 3–5%. For the use of recycled gypsum as a secondary raw material in gypsum production, the material has to be dried. The energy consumption during this drying process is included in the environmental evaluation. The drying of the material before calcination is also necessary for natural gypsum and FGD gypsum and part of the respective calculations. The different moisture contents of the investigated gypsum types (natural gypsum 1%, recycled gypsum 3–5%, and FGD gypsum 8–10%) affect the energy consumption of the processing and, accordingly, influence the results of the environmental evaluation [21]. The drying is performed after transportation to the gypsum producers and before calcination.

Besides the drying step, the production phase, including calcination, and the utilization phase are not part of this environmental evaluation in all four scenarios.

The system boundaries for the calculations of the environmental impacts from the production of natural gypsum were similarly determined. They included the following steps:

- recovery of natural gypsum from the deposits,
- transportation to the gypsum plant,
- the drying process,
- transportation to the costumer,
- transportation to a landfill after the use phase, and
- landfilling.

The system boundaries for the production of FGD gypsum were similarly determined. They included the following steps:

- transportation to the gypsum plant,
- the drying process,
- transportation to the costumer,
- transportation to a landfill after the use phase, and
- landfilling.

In contrast to RC-gypsum, the system boundaries of natural and FGD gypsum include the steps of transportation to a landfill after the use phase and landfilling. These steps are not necessary for RC-gypsum, because in this scenario, a recirculation of the material is included.

2.3. Life Cycle Inventory

The data collection for the inventory analyses was conducted in cooperation with recycling companies and equipment manufacturers. Accordingly, the used data were taken from industrial-scale productions. Further data were primarily taken from the life cycle inventory (LCI) database ecoinvent v 3.1 [39].

The geographical frame of the evaluation is Germany. Therefore, relevant datasets for Germany (such as the German electricity mix) were used. Further data for the calculations (e.g., for auxiliary materials in the production) were also taken, as far as possible, related to production in Germany.

The transportation distances were assessed on the basis of the known average values for the different existing routes and our own estimations.

Natural gypsum:

- transportation to the gypsum plant: 20 km
- transportation from the gypsum manufacturer to the costumer/construction site: 200 km
- transportation to a landfill after the use phase: 30 km FGD gypsum
- transportation of the GPW (from construction sites or collection points) to the recycling plant

2.4. Applied Impact Categories

With regards to already existing studies and further recommendations, the seven impact categories shown in Table 1 were chosen [3,40,41]

Table 1. Impact categories and related units.

Impact Category	Unit
Global warming potential (GWP)	kg CO_2 equivalents
Acidification potential (AP)	kg SO_2 equivalents
Eutrophication potential	kg PO_4 equivalents
photochemical ozone creation potential (POCP)	kg ethylene equivalents
abiotic depletion potential ($ADP_{elem.}$)	kg Sb equivalents
land use transformation	points
Land use, total	points

Consistent with international practice, the impact category global warming potential was evaluated using the CO_2 equivalents (100 years) with regards to the Intergovernmental Panel of Climate Change (IPCC) [42]. The impact categories' acidification potential (AP), eutrophication potential (EP), photochemical ozone creation potential (POCP, summer smog), and abiotic depletion potential ($ADP_{elem.}$) were calculated with the characterization factors given in the impact assessment model CML 2015 method [43].

Land usage and the threat to nature and the biodiversity were perceived using the ecosystem damage potential (EDP) with the categories land transformation and total land use [44,45].

3. Results

The results of the calculations are subdivided into the seven investigated impact categories. The specific figures map the results of each scenario divided into the values for each specific step: processing, transportation, and landfilling. The step processing includes the drying of the gypsum but, also, the extraction for natural gypsum and the associated upstream impacts from the applied materials and energy. Transportation includes the associated upstream impacts as well. Regarding the step landfilling, the use of machines and the upstream impacts of diesel and, e.g., lubricating oil influence the results as well.

3.1. Global Warming Potential (GWP)

In the impact category for climate change, FGD gypsum shows the highest environmental impacts, resulting from transportation, landfilling, and drying. The outcomes for recycled gypsum in comparison to natural gypsum are dependent on the transportation distances. The emissions are related to the diesel consumption during transportation and landfilling. The results for the four scenarios are shown in Figure 4.

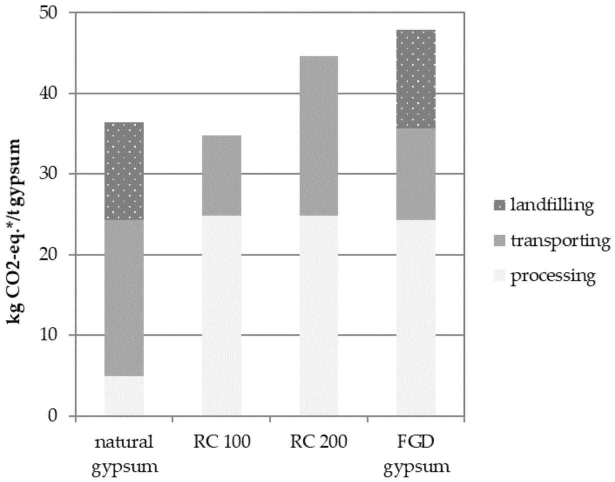


Figure 4. Results for the global warming potential. eq.*: equivalents

3.2. Acidification Potential (AP)

Figure 5 presents the results of the impact category acidification for the investigated scenarios. The electricity for the processing of recycled gypsum has a significant input to the acidification potential, due to the lignite-based generation of electricity in Germany. The AP of FGD gypsum is between the two RC-gypsum scenarios and is particularly influenced by the diesel used in the landfilling procedure and the transportation.

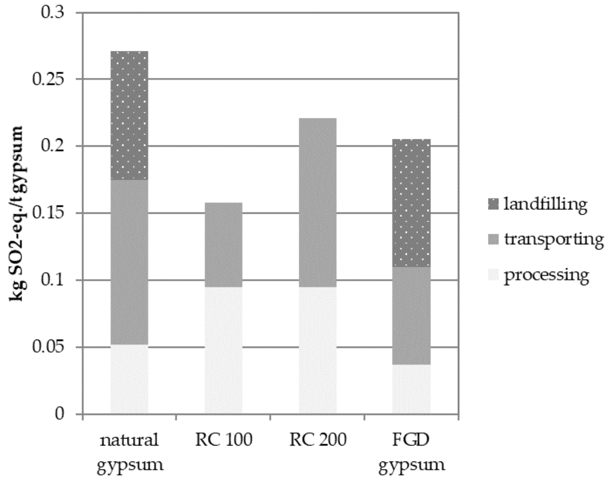


Figure 5. Results for the acidification potential.

3.3. Eutrophication Potential (EP)

In Figure 6, the results for the calculations of the eutrophication potential are shown. This impact category is dominated by the use of electricity for the processing and, also, by the high proportion of lignite-based resources in the German electricity mix. Compared to natural gypsum and FGD gypsum, both scenarios for recycled gypsum show a significantly higher eutrophication potential.

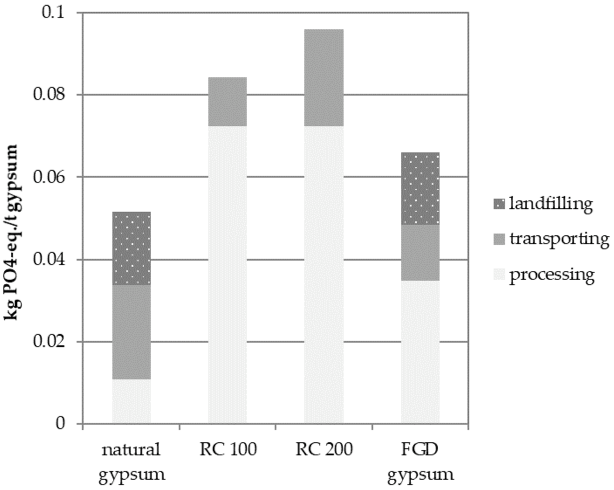


Figure 6. Results for the eutrophication potential.

3.4. Photochemical Ozone Creation Potential (POCP)

The impact category photochemical ozone creation potential is also dominated by the emissions caused by transportation and landfilling. Unlike in the category global warming potential, the scenarios for RC-gypsum outperform the scenarios for natural and FGD gypsum (see Figure 7). Although the emissions linked to the energy consumption during the processing of RC-gypsum are higher than those resulting from the processing of natural and FGD gypsum, the overall POCP for RC-gypsum shows a better performance.

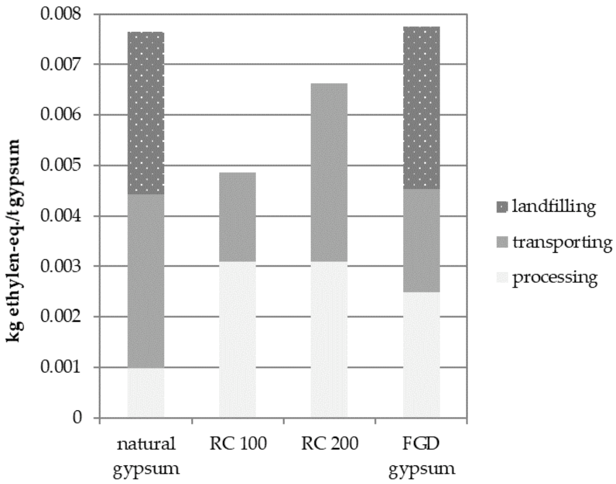


Figure 7. Results for the photochemical ozone creation potential.

3.5. Abiotic Depletion Potential ($ADP_{elem.}$)

This impact category represents the use of abiotic elements and is dominated by the consumption of natural gypsum and the related depletion potential (see Figure 8). Other resources, like metals, are negligible. Therefore, the ADP_{elem} of transports and landfilling are comparatively low and are summarized for use in Figure 8.

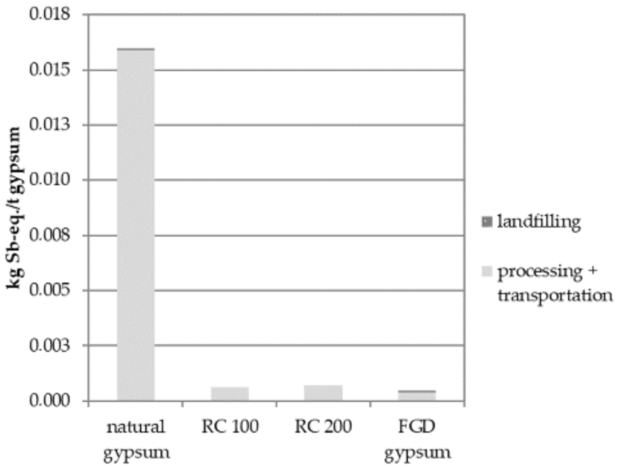


Figure 8. Results for the eutrophication potential.

3.6. Ecological Damage Potential (EDP): Land Use Transformation

The impact category land transformation is mainly influenced by the use of near-natural forests during the quarrying of natural gypsum, whose extraction sites in Germany are often located in the areas of old beech forests (see Figure 9). Renaturation measures cannot compensate for the ecological damage completely. The values calculated for landfilling are derived from converting other areas into landfill sites.

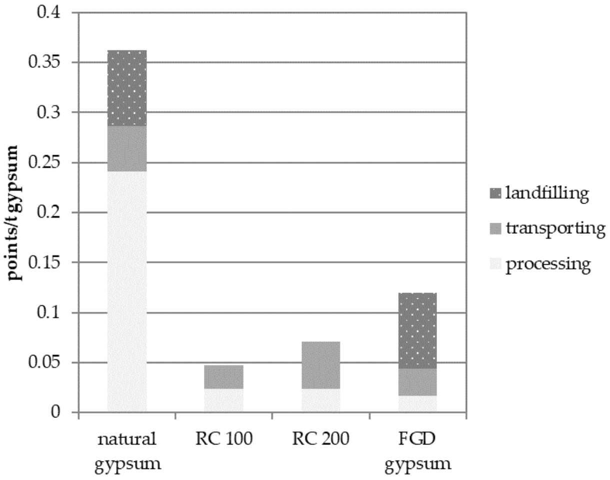


Figure 9. Results for land use transformation (ecosystem damage potential (EDP)).

3.7. Ecological Damage Potential (EDP): Land Use, Total

In contrast to the impact category "land transformation", which contains changes in the quality of land after usage, the category "land use, total" stands for the complete land use (Figure 10). The values for recycled gypsum caused by processing are comparatively higher. This is mainly due to the use of lignite-based electricity and the related usage of lignite mining sites. As a result of the land usage for landfilling and the land use caused by upstream chains from the production of landfill sealings, the total land use of natural gypsum is higher than for both recycled gypsum scenarios. The total land use for the production of FGD gypsum is in the same range as for the RC 200 scenario.

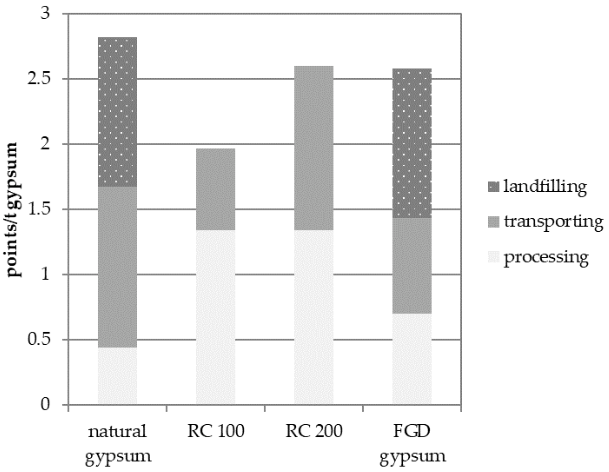


Figure 10. Results for land use, total (EDP).

4. Discussion

The evaluation of the environmental impacts of the recycling of gypsum waste on an industrial scale shows—in comparison to the results for natural and FGD gypsum—a predominantly positive but differentiated picture.

The calculations for RC 100 gypsum displayed the best results in the following five (of seven) impact categories: GWP, AP, POCP, land use transformation, and land use (total). RC 200 gypsum showed better results than natural and FGD gypsum in the categories of POCP and land use transformation and overperformed natural gypsum in the categories of AP and land use (total). Furthermore, the results for RC 200 gypsum in the impact category of GWP were better than for FGD gypsum. Regarding the eutrophication potential, the impacts of RC 100 gypsum and RC 200 gypsum were larger than those of natural and

FGD gypsum. This can be explained by the German electricity mix, which included a comparatively higher proportion of lignite-based electricity. The extraction of natural gypsum is the most influential parameter in the impact category $ADP_{elem.}$. Therefore, the resulting value for natural gypsum is several times higher than the values for RC-gypsum and FGD gypsum, which are approximately at the same level.

The results show that transport distances and landfilling have a significant influence on the calculation results of the impact categories of GWP, AP, POCP, and land use total. This can mainly be explained by the environmental effects of diesel consumption. Another factor is the avoiding of landfilling as a result of gypsum recycling in the corresponding scenarios. Furthermore, it is important that the input flows of FGD gypsum and gypsum waste into the respective system boundaries are unencumbered, due to their origins as by-products. The use of secondary raw materials and the related waste reductions have a calculable positive effect on the results of environmental evaluations.

Previous studies have stated that the environmental impacts generated by GPW recycling are clearly lower than the comparative values in all inventory categories. Several authors from Spain, the country with the largest gypsum production in the European Union, came to this result [13,33,34]. Compared to these studies, it must be stated that the results of our calculations seem to be not so straightforward. Besides the use of different calculation methodologies, this can be explained by several facts. On one hand, these studies calculated their tests with considerably shorter transportation distances, which affected the results, especially by avoiding emissions due to diesel consumption. On the other hand, in our study, post-consumer GPW was recycled, which means, that—compared to the recycling of pre-consumer gypsum—this material contains more impurities, and greater efforts during processing are necessary. Furthermore, in Germany, the quality standards for recycled gypsum that must be met are comparatively higher. This study showed that the recycling of post-consumer gypsum is feasible and can be environmentally advantageous. However, the importance of a good presorting accuracy on the construction sites should be emphasized. Therefore, good communication between the demolition contractor and gypsum recycling company is required to keep the amount of occurring waste materials low.

The development of new sources for gypsum is a further important element for future gypsum production. Therefore, the authors are going to investigate the usability of synthetic gypsums from industrial wastes (e.g., phosphogypsum or gypsum from food production) and, also, from gypsum fiberboards. An environmental evaluation of the different investigated recycled gypsum types will also be an important part of that work.

Since the electricity mix in Germany will change due to the planned shutdown of coal-fired power plants, it can be expected that the environmental impacts related to electricity consumption will decrease. In the upcoming years, the share of renewable energy in the German energy mix should lead to a better performance of recycled gypsum in the impact categories EP, AP, and, also, GWP.

5. Conclusions

Working towards greater resource efficiency in the construction sector is essential for addressing global issues such as slowing climate change and moving towards a circular economy. Therefore, the recycling of building materials is of particular importance. Based on the findings of this evaluation, it can be stated that the recycling of post-consumer GPW from the construction industry is feasible. Furthermore, although the meeting of high-quality standards is essential, the procedure, including comparatively long transporting distances, can be environmentally advantageous compared to the investigated natural and FGD gypsum scenarios.

Especially in Germany, where a replacement of FGD gypsum in the upcoming years will be required, recycled gypsum is of increasing importance. The results presented in this study showed that GPW recycling on an industrial scale can be eco-friendly. Additionally, the need for a substitute for FGD gypsum is expected to lead to further GW recycling facilities and, accordingly, to a development of transport logistics and a related reduction of transport distances. Furthermore, the expected changes in the German electricity mix will make the recycling of GW even more environmentally friendly.

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