Title: Closing the upcoming EU gypsum gap with phosphogypsum

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The EU Renewable Energy Directive with climate and energy goals does not leave room for coal-burning power plants that currently contribute approximately 17 million t of flue gas desulfurization (FGD) gypsum to EU manufacturers that require a total of 57 million t of gypsum per year (EU, 2020). It is also unlikely that natural gypsum production in the EU can be significantly increased in the near-term. Unlike other critical raw materials (CRMs) such as rare earth elements (REEs) that constitute a relatively small volume and can be imported over long-distances, such practice is not economically feasible for this relatively inexpensive (per weight) bulk-commodity used in large quantities. Transport costs for natural gypsum easily surpass the product value, so that imports would measurably increase prices for construction in the EU and affect millions.

In Germany, the largest producer and consumer of gypsum in the EU (roughly 10 million t/year), FGD gypsum accounts for 44% of all pro- cessed gypsum, 54% is attributed to natural gypsum, and 2% to recycled (RC) gypsum (Demmich, 2021). Germany's coal exit law will result in a shutdown of all coal power plants by 2038 and, therefore, an end of FGD gypsum production. How the 4.4 million t "FGD gypsum gap" in Ger- many will be filled, is unclear as of now. Although the coal exit law will hit Germany's gypsum processing industry particularly hard, similar shortages will be experienced and already occur in all EU countries that are closing coal power plants or have done so already. This will affect 21 of the 27 EU countries directly as these countries are operating coal power plants today and all others indirectly because of the EU internal market structure. The "FGD gypsum gap" in Germany

alone will already affect all EU members when German producers continue buying ever-larger amounts of natural gypsum from neighboring countries. Increasing the demand for gypsum there and thus putting pressure on the price of this valuable raw material. The EU already acknowledged this looming crisis by the increasing importance of natural gypsum and the underlying explanation in the most recent list of the EU CRMs (EU, 2020).

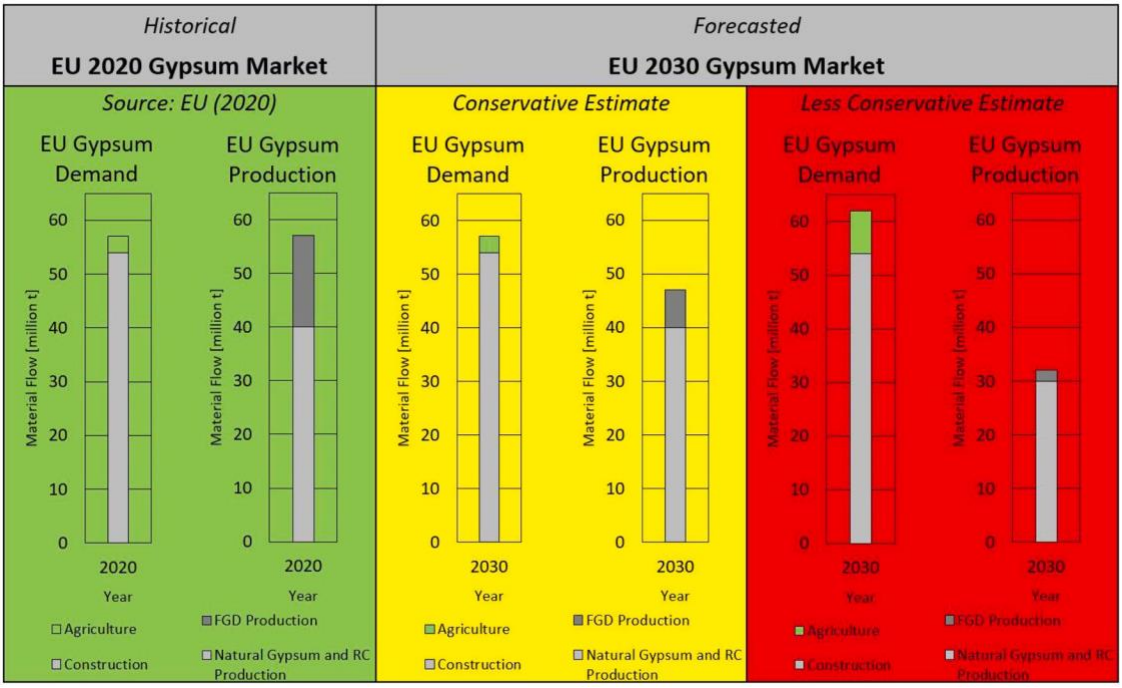

Fig. 1. Historical EU 2020 gypsum market (green column), as well as forecasted conservative (yellow column) and less conservative (red column) estimates of the future EU 2030 gypsum market.

Gypsum is widely used in construction and is the biggest sectorial employer in the EU. The European gypsum industry has a turnover of around EUR 7.7 billion. It operates 154 quarries and 160 plants, which generate direct employment for 28,000 people and indirect employment for another 300,000 people. The number of plasterboard installers alone in the EU is around 1.1 million, and it is estimated that the industry trains around 25,000 people per year (Marlet, 2018). As a result of the importance of the gypsum industry for the EU, predictions about future gypsum use can be considered fairly accurate (even in the light of the ongoing covid pandemic) and it is generally foreseen that gypsum de- mand for construction in the EU will remain fairly constant with a slight increase of 0.5–2.0% per year until 2030. In 2020, the EU used a total of 57 million t of gypsum for: (i) plasterboard and wallboard production (51%), (ii) building plaster production (26%), (iii) cement production (17%) and (iv) agriculture (6%) (EU, 2020).

Although the future use of gypsum in construction in the EU can be predicted with high certainty, the future demand for gypsum in agri- culture, which could be vast and reach levels equally high as the current use of gypsum in construction by 2040 (as speculated by Layr and Hartlieb, 2019) is not yet clear. Layr and Hartlieb, 2019 explain that the expected increase in soil salinization in Europe due to climate change could lead to a higher demand for gypsum as a soil amendment. A problem that will affect most EU countries to at least some degree in the near future. The same authors estimate that up to 39.6 million t of gypsum may be required in EU agriculture in 2030 to combat soil sali- nization.

They expect the amount of gypsum required in agriculture to increase further so that it satisfies the current demand for gypsum for construction in the EU of 53.8 million t by 2040.

The historical and forecasted balance of gypsum demand and pro- duction in the EU is illustrated in Fig. 1. Demand for agriculture and construction is shown to the left of each colored column, and the EU gypsum production from FGD gypsum and natural gypsum, including RC gypsum, is shown to the right. The demand of 57 million t gypsum in 2020 could be met by an equally high gypsum production (EU, 2020). The conservative estimate (Fig. 1 center) will see the coming EU gypsum gap at approximately 10 million t per year in 2030 (constant 54 million t use in construction, constant 40 million t natural/RC gypsum production, still 7 million t FGD or half of the 2020 level from coal power plants, and a constant 3 million t use of gypsum in agriculture). A less conservative estimate (Fig. 1 right) will see the coming EU gypsum gap at approximately 30 million t per year in 2030 (constant 54 million t use in construction, decline to 30 million t natural/RC gypsum production as a result of environmental regulations and resource depletion, 2 million t FGD as a result of coal power plant shutdowns in the EU, and 8 million t gypsum use in agriculture as a result of increased soil salinization).

Obviously, both numbers are estimates from several educated guesses that are prone to uncertainties. Undisputed is, however, the fact that there will be a gypsum gap in the EU and it is worth discussing how it can be closed.

Phosphogypsum (PG), a by-product of the mineral fertilizer industry usually wet- or dry stacked next to fertilizer plants but presently not processed on an industrial scale in the EU, could be a valuable substitute for natural gypsum and FGD gypsum. Approximately 2 billion t of PG are accessible for processing in the EU alone, with another 3–4 billion t being accessible for processing outside the EU. Most of these PG stacks outside the EU are found in Northern Africa, where they might be within economic reach of the EU market. Although this PG is often (depending on national regulations) classified as technologically enhanced naturally occurring radioactive material (TENORM) or low-level radioactive waste material, only 15% of the stacked PG actually shows radiation levels above legal limits (Layr and Hartlieb, 2019). The challenge is to find an inexpensive way to sort and process the vast majority of PG into useful gypsum. Ideally, with recovering the considerable amounts of REEs also present in the gypsum matrix (Gaustad et al., 2021).

We recommend that the EU acts today so that there will be a chance to close the upcoming EU gypsum gap tomorrow. Applied interdisci- plinary research with a strong industrial focus should be preferred to make PG available as an economically competitive gypsum substitute that can be used in construction and agriculture, fulfilling national regulations in EU member countries and elsewhere. Such a practice would not only make presently unused resources available and has the potential to close the upcoming EU gypsum gap but could also help substitute for a significant share of natural gypsum mining and all its unwanted environmental effects in the EU.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References:

Layr, Kathrin, Hartlieb, Philipp, 2019. Market analysis for urban mining of phosphogypsum. BHM Berg- und Hüttenma¨nnische Monatshefte 164, 245–249. https://doi.org/10.1007/s00501-019-0855-8.

Marlet, Christine, 2018. Gypsum sourcing: forthcoming challenges and recommendations. Symposium on availability of raw materials from secondary resources: a key aspect of circular economy. Symposium on the Availability of raw materials from secondary sources - a key aspect of circular economy. 24. April 2018, Palais des Nations, Geneva, Switzerland. GenevaApril.

Demmich, Jo¨rg, 2021. Auswirkungen des Kohleausstiegs auf die Gipsversorgung

Deutschlands. REWIMET Symposium 2021 Ressourcenmanagement. 25.-26. August 2021. Clausthal-Zellerfeld, Germany. 2021.

Gaustad, Gabrielle, Williams, Eric, Leader, Alexandra, 2021. Rare earth metals from secondary sources: Review of potential supply from waste and byproducts.

Resources, Conversation & Recycling 167, 105213. https://doi.org/10.1016/j. resconrec.2020.105213.

EU (2020) European Commission, Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, Blengini, G., El Latunussa, C., Eynard, U., et al., Study on the EU's list of critical raw materials (2020) : final report, Publications Office, 2020, https://data.europa.eu/doi/10.2873/904613.