OVERVIEW ON LCA: CHALLENGES AND OPPORTUNITIES FOR THE REFRACTORY INDUSTRY

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ABSTRACT

Organizations are now integrating life cycle thinking tools and techniques into decision-making to enable an analysis of the environmental impacts associated with all stages of a product's life. In this context, mining has been questioned by the widespread consensus that reducing resource consumption is a requirement for sustainable development. On the other side, it is clear that, due to dissipation, virgin raw materials will always be needed, and that circular economy thinking should integrate the mining industry and not oppose it. From this emerges the concern of resource depletion and the abiotic depletion potential (ADP) comes therefore as an attempt to assess the risk of depletion within life cycle assessment (LCA) methodology. However, when it comes to mineral resources, a lot of general assumptions are made, and the specificities of each element are often neglected. By attempting to include anthropogenic stocks in the calculations, some authors also neglect the singularities of each product. LCA has proven to be a powerful tool and its successful application within the refractory industry depends on collaboration between organisations in order to fill the numerous lacks of data availability and to overcome the challenges ahead. This paper is part of a PhD project that aims to build a database of magnesia production, from the mine to the kiln, to support LCA as well as to discuss resource depletion within the methodology and to account for the benefits and challenges of refractory recycling, focusing on magnesia bricks.

INTRODUCTION

The Circular Economy (CE) concept is increasingly gaining ground in academia and industry. Sustainability is the key word of our times and is leading the trend to increase circularity throughout all the stages of the production processes (Fig. 1). To achieve such a bold goal, it is important to know well and have a systemic vision of the whole life cycle, from the raw materials to the end-of-life (EoL), accounting for the origin of the main dissipative flows and environmental impacts.

Fig. 1: Representation of a product life cycle, Source: EIT Raw Materials

Life Cycle Assessment (LCA) has gained relevance in many industrial sectors as a sustainability tool. The methodology is used in different maturity levels within the industries, but it is generally recent. It is a powerful tool to get a better picture of the whole production chain and to help decision-making and redesigning of a product or process. Knowledge has advanced through the development of scientifically valid life cycle inventory (LCI) databases and models (e.g., EcoInvent), but some industrial sectors have still no significant or reliable inputs. Therefore, this is an open field with plenty of opportunities to be developed and intensive work will be required to face the challenges that will come with it.

The refractory industry is not out of it, but the LCA of refractory products is still in its infancy. Refractory linings are required in a lot of high-temperature production processes (metals, glass, cement, etc.). Therefore, refractories are part of the production of many essential materials for the civilization. Additionally, refractories have a significant CO_2 footprint, especially due to the calcination of magnesite ($MgCO_3$) to produce magnesia (MgO), one of the main raw materials (Eq. 1). Furthermore, the harsh corrosive conditions to which refractories are often exposed during their service life result in high dissipation rates, which affects circularity.

$$MgCO_{3(s)} \rightarrow MgO_{(s)} + CO_{2(g)} \qquad (1)$$

LCI databases have been created but seem still inconsistent and/or incomplete that professionals prefer not to use them and trust on their internal data, even though it may not represent a global extent. Additionally, relevant stakeholders are still not interested in overall environmental data, which limits the added value of LCA. Instead, customers are increasingly interested in Product Carbon Footprint (PCF) due to the growing pressure to decarbonise their whole value chain. Despite the given lack of interest in full environmental assessments, it can be expected that regulations can encompass an overall environmental impact of products in the near future. Therefore, given the importance of the refractory industry and the significant environmental impacts associated with it, efforts should be made to promote the use of LCA tools to provide a better picture and support decision-making towards sustainability.

REFRACTORY INDUSTRY: A SPECIAL CHALLENGE

Refractories present a major challenge to LCA practitioners due to their complexity. There is a wide variety of refractory products with distinct compositions and production processes. Unlike ordinary clay bricks, refractories have a wide range of raw materials between aggregates, binders, and additives. RHI Magnesita, the global leader in refractories manufacturing, uses more than 6,000 raw materials from many types of sources to produce more than 200,000 different refractory products. This is the order of magnitude of the challenge that needs to be addressed.

Moreover, very often some steps of the production chain are neglected or poorly documented in the literature. For example, it is common to find simplified representations of the production chain of magnesia from magnesite that obliterate the mineral processing step right after mining. The availability of high-quality data is fundamental for the assertiveness of the LCA study and therefore, industrials should think more collaboratively to fill the lacks that actual databases have. In the complex context that the refractory industry presents, only collective and centralized efforts would produce satisfactory results.

RAW MATERIALS SOURCING

Given that dissipation is inevitable in every step of a production process, many industries are often concerned about supply risk since virgin raw materials will always be necessary to feed the loop. Getting to know the production process and its required inputs is a first step that, followed by a detailed study of the raw materials sources, can give a more accurate scenario to help strategic decisions. Abiotic Depletion Potential (ADP) is a method within LCA that aims to account for the risk of depletion of elements with characterisation factors based on the ratio of the annual extraction rate (DR) to the square of the assumed stock (R) of a given element [22]. Antimony was chosen arbitrarily as a reference element to make a normalization of the results as shown in Equation 2.

$$ADP_i = \frac{DR_i / (R_i)^2}{DR_{ref} / (R_{ref})^2} \qquad (2)$$

Despite the simple calculation, the determination of the assumed stocks can be challenging, especially in the case of diverse potential sources and uses of the same element. In addition, since the methodology focuses on the very long run, an estimation of stocks should also consider a technological development that could make available some sources that are currently unavailable due to technical and economic constraints. To do so, there is no objective answer, and this subject is still an open discussion among experts.

Given that there may be more than one source and/or functional mineral of a given element, crustal content seems to be the best base for the calculation, since it refers to the element. Additionally, crustal content is the only reliable and stable base to estimate the stocks [3]. Regardless of the criteria used to determine the stocks in a long-term perspective, very often authors generalize it for different elements (e.g., same crustal depth). This is not geologically reasonable since different elements may have distinct origins, with different types of mineralization, varying the size, shape, and depth of the deposits. The generalization is also not economically supported, since elements may also have different values, not being able to afford the same extraction/processing costs. It is inconceivable to expect companies to dig as deep for limestone as they do for gold, due to the discrepant added values between these commodities. In the same way, it is unimaginable to find bauxite as deep as we find copper, given the differences in the geogenesis of these mineralisations.

Moreover, crustal content may mislead if applied disregarding the cut-off grade, i.e., the minimum concentration that allows the processing of a given element with the actual technology. Still, as ADP refers to a very long-term, technological development should be expected, enabling deeper mining and processing of poorer ores. Finally, economic, geological and technological constraints must be considered in the analysis.

A closer look into Magnesia

Due to its high melting point (2800°C), magnesia is one of the most important refractory aggregates. Mainly used in steelmaking, magnesia is obtained from the calcination of magnesite in most cases (Eq. 1). Developed countries without commercial magnesite resources typically produce magnesia from seawater, brines, or evaporitic deposits, which are common sources for the production of magnesium metal [19]. Magnesia produced from these sources is often called "synthetic magnesia", and "natural magnesia" is commonly the name given to the one obtained from magnesite. The concentration of magnesium in seawater is 1290 ppm [4] and high-purity magnesia can be obtained from it, but with significantly higher costs. Synthetic magnesia production requires up to twice the energy needed in natural magnesia production [18].

The share of synthetic magnesia in the global magnesia production capacity has decreased due to the tough competition with the Chinese market resulting in closures and a significant decrease in synthetic magnesia production capacity. However, due to the return of market growth, substantial investments were made in 2010, resulting in synthetic magnesia production capacity increasing, but remained a minor part of the share with magnesite source [19]. Figure 2 shows the global production capacity share between natural and synthetic magnesia in 2001 and 2013. Experts estimate that synthetic magnesia may represent around 10% of the actual global magnesia production capacity.

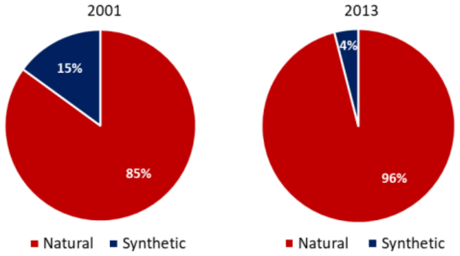

Fig. 2: Global production capacity of Natural and Synthetic magnesia, 2001 and 2013 [19]

With the increasing urgency of tackling climate change, alternatives to natural magnesia with a lower CO_2 footprint should now receive more attention. Besides seawater and brines, it has been shown to be possible to produce magnesia from Mg-bearing minerals either by mineral digestion followed by brucite ($Mg(OH)_2$) precipitation and further calcination [21] or by carbonation [11]. These processes are highly energy intensive and present higher CO_2 footprint than the natural magnesia mainly due to the available energy sources. Therefore, fostering green energy production could enable the production of magnesia from alternative sources with considerably lower CO_2 footprint. Combined with that, improvements are needed to achieve a production scale that would meet the industrial demand and increase the market share of synthetic magnesia.

Anthropogenic Stocks

With the growing stimulus to establish an industry that follows the principles of circular economy, it is important not to disregard anthropogenic stocks when evaluating resource depletion. Elements are not always used or dissipated, they can often still be available to be reused through recycling, which is also true for refractories. Therefore, Schneider et. al. (2015) [20] suggested that the ADP assessment should be broadened to encompass anthropogenic stocks in the calculation. The authors made no differentiation between the elements and a general dissipation rate was used. This is problematic because, in addition to the different behaviour of distinct elements, the same element may be used in multiple ways within the anthroposphere, resulting in multiple dissipation rates for the same element. That gives an idea of how complex the estimation of anthropogenic stocks can be.

Moreover, a point that must be highlighted is that not all the elements within the anthroposphere are available for eventual recycling due to long-term use. Consequently, occupation-in-use should be taken into account when trying to measure anthropogenic stocks [1].

Last but not least, in some cases the anthropogenic stocks may not be relevant because they may represent a minor part of the total stocks in the calculation of ADP. Thus, estimating the anthropogenic stocks to include in the ADP calculation may not be worthwhile for elements with high natural stocks and/or dissipation rates. Otherwise, it may be relevant in case of more scarce elements and/or with high recyclability.

RECYCLING

During the use phase, around 30-40 wt.% of the refractory is consumed [13], indicating that up to 35 million tons of spent refractories are generated every year from the 50 million produced [12]. The fact that refractories are corroded and dissipated during the use phase shows that primary raw materials will always be needed in the refractory industry because even with refractories completely made of recycled raw materials in a closed loop, the losses during the use phase would make it impossible to keep the production without using virgin raw materials.

Due to the abundance of virgin raw materials, in the past, recycling received little attention in refractories manufacturing. Added to this, the low disposal costs of the, largely inert, spent refractories was another reason to keep the refractories recycling out of focus. Instead, a lot of progress was made in the refractory consumption per ton of product. In the steel industry, refractory consumption has declined from 25-30 kg of refractory per ton of steel in the 1970s to 8 kg/t today in US and Japan [2]. Such progress could be seen also in other industries as the production of cement, which decreased the relative refractory consumption from more than 2 kg per ton of cement clinker to on average 0,9 kg/t [5].

With the increasing landfilling costs and environmental concerns, recycling has risen as a strategic alternative to guide the refractory industry towards a circular economy. Spent refractories have been largely used in open-loop recycling applications such as roadbed aggregates [2] and slag conditioners in the steel industry [8]. In these applications, the value of the recycled material is limited to the cost of the replaced material, which is much cheaper than refractories.

However, closed-loop recycling is still limited to an average of 7% of refractory raw material demand [15]. Recently, RHI Magnesita has increased the global recycling rate to 10.5% in 2022 [16]. Studies showed that the production with 20% of recycled refractories as raw material is achievable in the manufacturing of LC series [9]. Remanufactured MgO-C bricks containing up to 30% of recycled material were found to have almost the same properties and durability as low-grade MgO-C brick [13]. More recently, Kunanz et al. (2022) [10] reported a successful implementation of high recycling containing magnesia-carbon brick in steel ladles. The newly developed brick contains 87 wt.% of recycled material and reduced the long-term average consumption from 0.21 kg/tonne steel to 0.13 kg/tonne steel, a reduction of 38% of refractory material use.

The substitution of virgin raw materials for recycled spent refractories leads to a considerable reduction in the carbon footprint since the thermal treatment of magnesite and dolomite includes the most CO2-intensive processes. The production of dead burned magnesia (DBM) and dead burned Doloma (DBD) is responsible for around 85% of RHI Magnesita's scope 1 emissions. In 2020, the production of DBM and DBD generated approximately 1.8 million tons of CO_2 scope 1 emissions, of which 60% were geogenic and 40% were fuel-based [17]. A standard magnesia-carbon brick has a CO_2 footprint of 3.95 tonne CO_2/tonne bricks, while an 87% recycled content magnesia-carbon brick has only 0.55 tonne CO_2/tonne bricks, an expressive reduction of 85% [10].

Nevertheless, refractories recycling can be challenging. During their lifetime, the refractories undergo some modifications in their physical and chemical properties, especially in their exposed surface, due to the usually hard operating conditions. Refractories may then have some inclusions of slag or metals and then, the content of CaO, Fe_2O_3 and SiO_2 also increases in the spent magnesia-based refractories used in steelmaking. Therefore, this increase can also be seen in recycled refractories [7]. The presence of these impurities typically leads to a decrease in durability because of melt formation between Ca/Si and Mg/Al [6]. Furthermore, recycled refractories aggregates tend to present higher porosity and lower density than virgin raw materials, which affects their physicomechanical properties and limits the amount of recycled refractory aggregates that can be introduced into the refractory mix [7].

In addition, as most of the furnaces use more than one type of refractory product, it becomes difficult to separate the different refractories when removing the spent lining and in most of cases they are indiscriminately mixed into a pile. Therefore, processing spent refractories to improve refractory recycling faces the challenge of sorting different types of refractories. The state-of-the-art recycling plant for refractory waste includes, therefore, a pre-sorting step, in which the different types of refractories are separated. This stage is usually done manually, and even after this sorting process different types of refractory materials are often mixed and contaminated with pieces of iron metal and slag [6]. This step is highly error-prone due to the presence of dust and other contaminants that limit the visual identification and because it is dependent on the operator's expertise [7].

Besides the lack of efficiency and objectiveness of the manual pre-sorting of spent refractories, the dusty environment and the hostile working conditions are other concerns. Therefore, there is a strong demand for automation in the pre-sorting step within the industry to improve accuracy and speed as well as the working conditions. Some systems have been developed based on colour sorting, however, it is hindered by the dust layers as well as the similar appearance of chemically distinct refractories. In the last years, sorting systems were developed using LIBS (Laser Induced Breakdown Spectroscopy), which uses a pulsed laser to ablate the surface of a material, typically penetrating around 100 µm deep into the sample, eliminating then, most of the surface interference caused by dust [7].

The European project REFRASORT successfully developed a LIBS system that aims to separate the main refractory types used in the steel industry, such as MgO-C with and without antioxidants, carbon-bonded doloma, fired doloma, bauxite, andalusite and chamotte [14]. A test was carried out using the REFRASORT demonstrator (Figure 3) with 30 t of mixed magnesia, doloma and alumina-based spent refractories [7]. The accuracy was validated by analysis of the output fractions and the sorted fractions achieved the targeted contents, being the only exception a slightly higher SiO_2 content in the doloma fraction.

Fig. 3: REFRASORT demonstrator system [7]

Recycling is one of the best strategies to reduce carbon emissions within the refractory industry and therefore it is one of the priorities of many refractory producers. The increasing environmental concern may motivate customers to push the refractory industry to develop green alternatives. In this context, some kind of sustainability certification of refractories will be of interest, since refractory consumers will be concerned about the global environmental impacts the products have. LCA is the right tool to produce that kind of summary and enable a more conscient consumption.

CONCLUSIONS

LCA is an important tool that can contribute to a better understanding of a whole production process in terms of supply and environmental impacts. It is a powerful method to enable a systemic vision and therefore to identify the main bottlenecks in the environmental performance of a product, allowing the eco-designing. By giving the big picture of a product, LCA can help industries to know their products and processes well enabling a more assertive decision-making towards sustainability.

However, it has been proven challenging to implement LCA within the refractory industry. There is still low reliability in the few databases created and the high complexity and variability of refractory products pose difficulties. To accomplish such a tough goal, collaborative efforts would be necessary between raw materials suppliers, refractory producers, and end users since data availability is still of concern.

Moreover, there is a lack of interest in LCA data from relevant stakeholders, which limits the added value of such assessments. Instead, PCF is increasingly in demand as companies come under small but growing pressure to decarbonise their entire value chain. Thus, from a regulatory perspective, linking taxation with the whole environmental footprint could be a possibility in the near future to push the industries to reduce overall environmental impacts, and then the refractory industry should be prepared to overcome this challenge, possibly by implementing LCA analysis.

In terms of supply, there is evidence that the ADP should be reviewed to assess the risk of depletion of raw materials more accurately. Every element should be addressed individually, accounting for its specificities, and avoiding generalisations. The assumed stocks have been a concept under discussion and hard to determine, given the subjectiveness of envisioning economic and technological conditions in a very long-term perspective added to the complexity of geological analysis. Alternative sources should be considered to avoid supply shortages and, in the case of magnesia, can offer the environmental advantage of avoiding high CO_2 emissions by producing synthetic magnesia instead of natural magnesia. The inclusion of anthropogenic stocks in the calculation of ADP seems to be relevant since recycling has been fostered in many industries. However, some improvements are still needed to do this coherently.

Recycling has proven to be an effective strategy to reduce the carbon footprint of refractories and to make the refractory industry more sustainable and circular. A lot of progress has been done in the past few years and an overall recycling input rate of 10.5% was achieved in 2022 at RHI Magnesita. Magnesia-carbon bricks made with 87 wt.% of recycled material proved to be functional, reducing the PCF by 85%. Many projects have been developed to improve the recycling of refractories and the LIBS technique delivered good results in sorting different spent bricks. Recycling seems to be the way to revolutionise the refractory industry towards sustainability.

OUTLOOK

This paper is part of a PhD thesis, within the CESAREF consortium, entitled *“Documenting the Upstream of Refractories Manufacturing to Support LCA”*. Since one of the challenges of implementing LCA within the refractory industry is the lack of availability of good quality data, the main goal of this project is to build a better knowledge about the production of refractory raw materials, more specifically, magnesia production. A description of the current and alternative production routes will be accompanied by an inventory of the main inputs and outputs of the production processes (CO_2 emissions, energy consumption, etc.). Parallelly, the project aims to discuss resource depletion within LCA, reviewing the ADP methodology and making an analysis focusing on magnesium. Finally, accounting for the benefits and challenges of magnesia bricks recycling with eco-design recommendations is another goal.

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