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Deliverable D1.3 - LCA of recycling processes of refractory materials, with eco-design recommendations

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1. Introduction and state of the art of refractory recycling

Refractories are ceramic materials able to withstand high temperatures in harsh conditions. The volume of refractories produced yearly is estimated at 35-40 million tonnes, of which around 70 % are used in the steel industry [1]. About 60-70 % of used refractories are available as waste after their usage [2], hence constituting a potential source of secondary refractory materials. However, only approximately 7 % of raw materials input was covered by recycled refractories in 2019 [1]. Favouring the recycling of refractory waste offers many advantages, from the conservation of natural raw materials and a lower reliance on raw material suppliers to reduced landfill disposal of waste [3]. Based on the quality of the secondary material, it is possible to distinguish between closed-loop and open-loop recycling. Open-loop recycling includes process routes where the recovered materials are used for applications other than the original one or when the waste is not fully valorised due to a change in its inherent properties [4]. On the contrary, closed-loop recycling entails recovering waste without altering its inherent properties, hence being potentially applicable in the same function as the initial product. Today, the most common open-loop recycling of refractory materials is for roadbed aggregates or slag conditioners. This type of recycling is also called downcycling, due to the lower quality and functionality of the recycled material than the original product and such a route usually generates lower environmental benefits and economic advantages. Indeed, the value of the recycled refractory is influenced by the cost of the replaced material [1]. Considering the price of recycled materials as 60-100 % of the respective raw materials [5], closed-loop recycling would guarantee higher economic benefits than downcycling, where high-quality refractories replace sand or other natural aggregates. In recent years, steelmakers have also shown interest in the internal and external reuse and/or recycling of refractory materials, which constitute around 7 % of all the by-products in the steel sector [6]. In the steelmaking industry, refractories are believed to be one of the core categories of future research for reuse and recycling [6]. Due to the joint interest of refractory producers and users towards recycling, much progress has been made to characterise the recovered materials and explore the potential recycling routes. However, only limited research was dedicated to quantifying the environmental performance of the recycling processes to verify whether the technical and economic feasibility of the process would correspond to considerable ecological gains. In general, the usage of recycled refractories is expected to generate environmental benefits, as a result of avoiding waste disposal as well as the extraction and processing of virgin raw materials. Two studies support this idea by quantifying the environmental performance of refractory recycling processes using Life Cycle Assessment (LCA) [7], [8]. LCA is a scientific multi-step tool that quantifies the impacts of products or processes on a set of selected environmental domains represented by impact categories. Both studies applied LCA to refractory recycling, but the different modelling approaches resulted in incomparable results. Both studies quantified the environmental burdens generated by the recycling treatments and the environmental gains from virgin material substitution. However, they only provided an aggregated analysis of the recycling treatments, with no process-level information. While Ferreira et al. modelled their system upon literature data, Muñoz et al. used data collected in a real plant, even though only four impact categories were addressed, hence providing a limited vision of the process's environmental performance[7] [8].

Within this context, the present project aims to advance the research on the environmental performance of post-consumer refractory recycling by detailing the recycling processes and updating the existing life cycle inventories. For the aim of comparability and harmonisation, a specific LCA

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methodology for refractories is proposed and tested by calculating the environmental performance of a state-of-the-art plant with process-level detail. In addition, eco-design recommendations are tested through scenario analysis. Lastly, the environmental loads and benefits from the substitution of various raw materials are compared.

Each of the abovementioned goals is the core of a section in the current report. Specifically, in section 2.1, the state-of-the-art processes for refractory recycling are described. Then, in section 2.2.1, the structure and application of LCA are introduced, with a focus on the key methodological challenges for modelling recycling in section 2.2.2 and the description of the approach chosen in this study. After the general introduction, the method has been applied to magnesia-carbon and high-alumina refractory waste, which are described in section 2.3. The section 2.4 is dedicated to the LCA of the two materials, with a description of the adapted recycling route (2.4.1), the related life cycle inventory (2.4.2) and the LCA results (0). It also includes eco-design recommendations for the reduction of environmental impacts of recovered materials (2.4.4). After analysing the environmental performance of the recycling treatments, the possible usage of recovered materials is briefly described in section 2.5.1. The potential benefits and loads from substituting virgin raw materials with recycled ones are quantified in section 2.5.2. Finally, the section 3 summarises the key findings of the report and proposes the next steps for future research.

2. Life cycle assessment of refractory recycling

2.1. Most common recycling processes

State-of-the-art recycling plants of spent refractories usually involve pre-sorting of the waste mix to divide the various refractory types, followed by separation steps aimed at removing impurities [1]. As shown in Figure 1, the spent refractories are manually pre-sorted, the separated fluxes undergo size reduction by crushing and/or grinding followed by separation processes such as magnetic, colour and gravitational separation. The purified waste is then divided into different size fractions through sieving and finally packed. The literature reported average recycling efficiencies of approximately 50 % to 70 % [3], [7], [9], [10], [11].

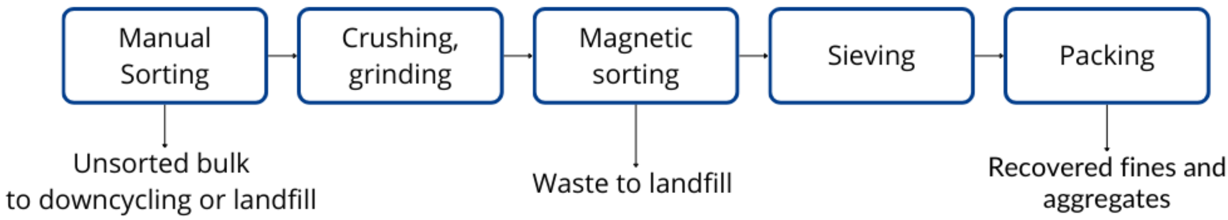

Figure 1 - Recycling process of spent refractories - General flowchart.

The refractory mix is supposed to reach the plant in a bulk shape (Figure 2a) and be temporarily stored outdoors (Figure 2b) before being manually sorted. The sorting involves separating the refractory types present in the input waste stream, which is fundamental to ensure good recycling rates and high quality of the recovered materials. Indeed, due to the variable composition and the presence of inclusions and pollutants, the unsorted material is difficult to reuse and, eventually, only destined for downcycling. Manual sorting relies on visual inspection by trained operators (Figure 2c) and becomes significantly more efficient when pre-sorting is performed at the steel plant through selective dismantling.

This sorting is only performed on aggregates with dimensions over 80 mm, hence losing a potential source of secondary materials in the unsorted fines [12]. Typically, the remaining unsorted flow is either landfilled or downcycled into products such as metallurgical additives, not valorising it fully. The choice guarantees the economic sustainability of the operation and the capacity of operators to efficiently distinguish different refractory aggregates. The current literature quantifies the unrecoverable fine fraction in a range of 25-40 % [9], [10], [11]. New automatic sorting techniques have been developed in the last years to improve the recovery rate by treating the smaller fraction (< 80 mm). In the Refrasort project, Laser-Induced Breakdown Spectroscopy (LIBS) sensors, capable of fast multi-element analysis, were combined with mechanical handling devices to improve the sorting of spent refractories [13]. Such a new method is expected to enhance the recyclable quota of refractories and their purity, hence providing high-quality recovered fines to be applied in high-performance applications, such as refractory production. However, further or more intense purification and separation treatments might be necessary, as the finer fraction was demonstrated to contain higher amounts of impurities [3], [14].


(a)


(b)


(c)

Figure 2 - (a) Spent MgO-C from steel furnace breakout [15]; b) Outdoor storage of spent refractories received at the recycling plant before treatments [16]; c) Manual sorting [17].

After sorting, the waste is sent to crushing and grinding to reduce the size of the particles. The type and intensity of the size reduction depends on the dimension of the input material, which depends on the dismantling procedure and is conditioned by the eventual dimension requirements of following separation treatments. Jaw and impact crushers are commonly used in primary crushing to break large pieces of refractory into smaller ones. Cone crushers and impact crushers are generally used for eventual secondary crushing to further reduce the size of the material. Then, separation processes are performed to remove the impurities from the crushed aggregates. All recycling plants include a magnetic sorting stage to remove metallic inclusions such as steel and slag. The conventional treatment is performed with a suspended magnetic separator over a conveyor belt, even though a puller-type magnetic separator configuration (band magnet) is more efficient in removing weak magnetic slags or minute iron components. The best configuration would combine both magnets [18]. In specific cases, especially for non-carbon-containing refractories, the removal of non-magnetic components can be performed by colour sorting. Some plants conduct further separation steps such as gravitational separation or floatation. For instance, air classification can be used to remove light-weight contaminants or to remove dust from the fine fraction. Also, fluidisation demonstrated promising results for both dust and carbon removal in the fine fraction [12]. After the purification stages, the recovered materials are separated into distinct size fractions and packed. Three types of packaging are used to dispatch the secondary raw materials: small bags with a capacity of around 25 kg, bulk bags with a capacity of 1000 to 2000 kg or no packaging at all (bulk transportation). Starting from the aforementioned generic recycling route, additional processes could be necessary to face material-specific challenges and application-related requirements. For instance, some authors suggested the need for drying the recovered aggregates before their application in the refractory or construction sector [7], [18], [19].

2.2. How to address recycling in LCA

2.2.1. Introduction to LCA methodology

The life cycle assessment (LCA) is a multi-step scientific procedure that quantifies the environmental impacts of products and processes. LCA is made up of four phases, namely goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA) and interpretation. The goal and scope phase establishes the purpose of the study and its methodological set-up. It also describes the targeted product system, or the ensemble of processes that characterise the life of a product, in terms of system boundaries and functional unit (FU). Following the goal and scope phase, the LCI phase quantifies the relevant inputs and outputs throughout the product system. The LCIA phase evaluates potential environmental impacts by associating the inventory data with environmental impact categories. The interpretation phase ensures the results align with the objectives of the study, also identifying uncertainties and improvement opportunities. To guarantee the comparability, consistency, reliability and transparency of LCA studies, standards were created to guide the methodological choices of LCA practitioners and harmonise the calculation of the environmental impacts. The international standard ISO 14040 [20] and ISO 14044 [4] provide the definitions, framework and principles for conducting life cycle assessment. This general framework could be complemented by other standards for specific LCA purposes, such as creating environmental declarations to support sustainability reporting and procurement decisions and guarantee regulatory compliance. The Environmental Product Declaration (EPD) is a standardised and internationally recognised tool widely used by companies to certify their materials' performance and communicate them to customers. Indeed, the market demand for products with lower environmental burdens makes the materials' environmental performance an asset for competitiveness, with a role almost as important as the technical performance in use. EPDs follow ISO 14025 [21] and sector-specific Product Category Rules (PCR). They are widely applied in the construction sector, following the PCR 2019:14 [22] and EN 15804+A2:2019 [23] standards. In this project, LCA is modelled upon the framework established for construction materials. Indeed, it has been chosen to follow EPD rules to propose LCA results which could be compared to the existing and future declarations on refractories, in other words, providing results easily accessible and usable for companies. Due to the lack of category rules for the refractory sector, the approach for construction materials is chosen based on the similarities of the refractory life cycle with some ceramic materials used in the construction sector.

2.2.2. The methodological challenges of LCA of refractory recycling

The life cycle assessment of recycling processes presents a methodological challenge in attributing, i.e. allocating, the environmental burdens between the recyclable end-of-life product and the resulting recycled material. The choice of the allocation approach and the definition of the system boundaries can have a decisive impact on the environmental assessment of both products, however, no consensus has yet been reached [24]. It could be argued that the choice of the best assessment method is not universal and is to be adapted to the targeted products and LCA goal. A first selection of allocation methods could be based on their compatibility with the attributional and consequential nature of the LCA. Attributional LCAs quantify the share of global impacts that belong to the targeted product or activity. Instead, consequential LCAs identify how the production and use of the product could generate environmental consequences due to market-driven changes and indirect effects beyond the immediate system. Such distinction is not purely theoretical, as it influences the choice of the system boundaries as well as whether and how incentives are given for waste recycling.

The attributional approach only requires allocating the environmental impacts of the primary production, recycling processes and final waste management between the products where the material is used. Recycling incentives related to avoided waste disposal and virgin material substitution are not considered, as they do not fit in the product system investigated, but rather belong to another product system. Conversely, the consequential approach requires evaluating to what extent waste disposal and virgin material production are avoided thanks to the use of recycled materials. Hence, consequential LCA typically involves the product system expansion to include the processes avoided through recycling. In this project, an intermediate method called the “cut-off plus credit” approach is applied to the recycling of post-consumer refractories. The cut-off approach, commonly used in attributional LCAs, allocates the environmental impacts of recycling activities between the original product being recycled and the new product that incorporates the recycled material. The boundary between the life cycles is placed at the end-of-waste point, where the recyclable material becomes a marketable product. The “plus credit” part of the method is more in line with a consequential approach and refers to expanding the assessed product system to calculate the potential benefits and loads caused by the net output of secondary materials and energy. However, the benefits and loads are declared separately and not accounted for in the system's environmental performance. The cut-off plus credit methodology was developed within the context of the EPD of construction materials [23].

Once the methodological framework is defined, recycling could be modelled from three diverse perspectives, focusing on the recyclable waste, the recycling activities or the recycled materials. The choice depends on the LCA goal and scope and influences the definition of the system boundaries and the calculation of the environmental impacts. In the first case, the recycling activities are a waste management technique in the cradle-to-cradle LCA of the primary product. The goal of the assessment is to evaluate the contribution of end-of-life management to the full life cycle of the product. In the second case, the purpose of the study is to quantify solely the impacts of the recycling treatments. Hence, a cradle-to-gate LCA of the recycling activities is performed to quantify the impacts of the recycled material production. In the third case, the effect of using recycled materials is investigated in the LCA of the product consuming them. The comparison of the product manufacturing impacts with and without recycled content quantifies the environmental effects of using secondary materials. This study focuses on the recycling treatments by performing the cradle-to-gate LCA of recycled refractory aggregates and fines. In addition, as a result of the cut-off plus credit allocation, indications are given on the potential environmental benefits arising from the substitution of virgin materials.

2.3. Chosen materials: magnesia-carbon and alumina bricks

Two products are studied to represent the recycling of refractories, namely spent magnesia-carbon bricks and high-alumina bricks. As it was not possible to model case studies based on primary data collected on-site, the type and composition of spent refractories were chosen from the literature. Magnesia-carbon (MgO-C) bricks are basic shaped refractories widely used in steelmaking in the wear lining, or the area in direct contact with steel and slag, of steel ladles, converters and electric arc furnaces. Their large diffusion is due to their resistance to chemical corrosion, erosion and thermal shock, as well as their low wettability, which makes them particularly suitable to protect the slag line [25]. High-alumina refractories (A) are alumina-silicate refractories that contain over 42 % alumina [26]. These products are further classified according to the quantity and type of alumina contained and the raw materials from which they were obtained. In steelmaking, high-alumina refractories are used in a variety of applications, from the wear lining of the roof of electric arc furnaces to the backup lining of steel ladles, hot metal ladles and tundishes, or the production of plugs. MgO-C and high-A refractories are part of the spent refractory flows that are recycled in remarkable quantities [13].

For the present study, it is assumed that the magnesia-carbon brick is fused-magnesia-based and resin-bonded, with aluminium powder as an antioxidant. Its composition is 82.5 % magnesia and 10 % carbon. The high-alumina refractory contains 80 % alumina, 10-15 % silica and 2 % iron oxide. No specific application has been identified for the two chosen materials.

2.4. Environmental impacts arising from the recycling of refractories

2.4.1. Product system definition

This chapter describes the cradle-to-gate LCA of magnesia-carbon and high-alumina shaped refractory recycling. The goal of the LCA is to quantify the environmental impacts of the recycling activities following the standards EPD 15804+A2 and PCR 2019:14. The product system assessed in this study is detailed in Figure 3. It includes the transportation of spent refractories from the steel plant to the recycling site, the recycling processes and the final waste disposal. The input refractory waste bears no burden, per the polluter pays principle, and the end-of-waste state is considered to be reached at the gate of the steel plant. Any eventual pre-treatment at the steelmaking site for the collection and preparation of the waste is allocated to the waste producer. It is supposed that a selective dismantling is performed at the steel plant, resulting in a waste mix containing mainly one refractory type.

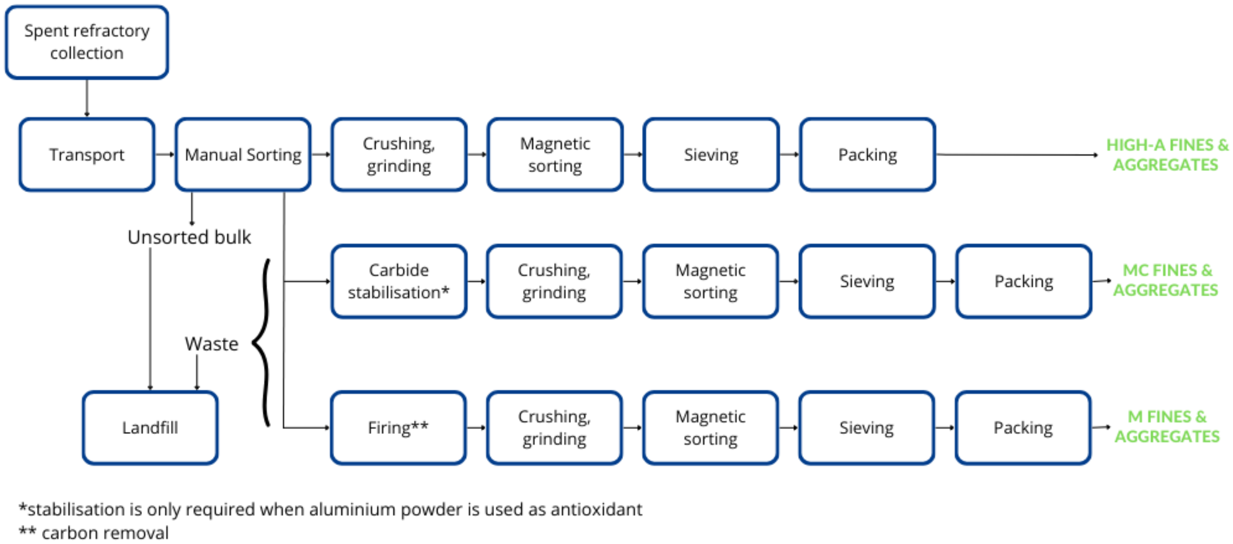

Figure 3 - Recycling route for magnesia-carbon and high-alumina spent refractories.

The processing of high-alumina waste follows the flowchart already presented in section 2.1 and includes manual sorting, crushing, magnetic sorting, sieving and packing. The recovered materials are diverse size fractions of aggregates with high-alumina content.

In the case of the magnesia-carbon brick, two process routes are studied. In the first case, MgO-C waste undergoes the same treatments applied to the alumina waste to recover MgO-C aggregates and fines. An additional stabilisation step is required to hydrate the aluminium carbide that forms in those MgO-C bricks containing metallic aluminium powder used as an antioxidant. During their usage, the bricks' exposure to heat favours a chain of reactions that transform aluminium into alumina, aluminium carbide and aluminium hydroxide. The aluminium carbide hydration and the aluminium hydroxide decomposition cause severe cracking and spalling in the recycled aggregates at high temperatures [27]. Forcing the hydration of the aluminium carbide during recycling prevents damage in the refractory containing the recycled MgO-C aggregates. One of the easiest techniques for carbide stabilisation is weathering, which consists of spraying water on the refractory waste and storing it outdoors for two or three months, exploiting the carbide’s high reactivity to water at atmospheric humidity and room temperature [28]. Some authors suggested replacing the weathering with thermal pre-treatment at 400 °C to speed up the process and have better control of the material quality [27]. The classical treatment is chosen in this study. The second recycling route for MgO-C waste involves a firing stage to remove the carbon content and recover secondary magnesia.

2.4.2. Compilation of the life cycle inventory

Data availability is a challenge for the LCA of refractory recycling. Despite the growing interest in recycled materials, the calculation of their environmental performance is recent and recycling plants are still adapting their on-site measuring systems to monitor mass and energy flows. Currently, aggregated data at the plant level are mostly available, preventing product-specific and process-specific assessments. Data collection is also complicated by the variability of the input waste composition and the difficulty in collecting representative samples that relate inventory flows to the material’s properties. In this work, it was not possible to directly collaborate with recycling plants to collect primary data, hence, the life cycle inventory is built upon literature and theoretical calculations. Therefore, the examples described in this project cannot be addressed as case studies, as they do not depict any specific existing plant. Nevertheless, they depict state-of-the-art refractory recycling routes.

All the background processes are modelled from the ecoinvent 3.9.1 commercial database, in the version "cut-off by classification".

Some material and energy flows are modelled at the plant level due to the impossibility of allocating the available data to the contributing processes. This is the case of the energy required by material handling and internal transport, modelled upon the ecoinvent 3.9.1 dataset describing the sorting plant of Construction and Demolition (C&D) waste. The electricity consumption of all conveyor belts in the plant is approximated from the same dataset, where it is aggregated with the consumption of the sieves. Lastly, the dataset quantifies the particulate matter emissions generated by all internal movements, material handling and sorting in the plant. The production of infrastructures and capital goods is excluded from the inventory, while the consumption of lubricating oil is approximated from the literature on C&D waste recycling. The waste refractory mix is supposed to arrive at the plant in bulk without packaging. It is assumed that no relevant emission to soil or air is released during the temporary storage, given the inert nature of the waste mix. Similar considerations are done for MgO-C weathering, which is modelled without burdens. The carbide stabilisation does not require energy, and the potential water and methane emissions to the air are ignored in this inventory. Indeed, as stated in [27], laboratory tests cannot provide a clear indication of the aluminium carbide content in post-consumer bricks. Also, stoichiometric calculations risk not being accurate due to the simultaneous reactions involving aluminium products. Instead, manual sorting only requires electricity for the conveyor belt transporting the waste to be sorted. The energy required for crushing refractory waste depends on many factors, such as the hardness of the material, the type of crusher, the dimension of the input waste aggregates and the desired output size. Two size reduction stages are considered, performed through a jaw crusher (crushing) and a rod-mill or bar-mill (grinding). The crushing energy intensity is approximated from the literature, while that of grinding is calculated using the Bond Work Index. The Bond formula calculates the crushing energy based on the size distribution of the feed and the product and a work index that represents how easily the aggregates are crushed [29]. Different indexes are provided for minerals and other materials depending on the dimension of particles. In this study, manual sorting imposes a minimum size of 80 mm for the aggregates to be crushed. The final desired dimension is assumed to be around 5-6 mm, coherent with the market demand. The request for smaller particles could be covered by the finer fraction automatically generated during crushing or obtained by the consumer on-site during raw materials preparation.

To conclude, the road mill work index from [30] is used to approximate the grinding energy. The calculations just described only provide a rough indication of the energy required for size reduction, hence, the improvement of the inventory is recommended in future assessments. However, despite the approximations, the total energy demand of the studied recycling routes is comparable with the literature on similar C&D waste recycling processes. Crushing is preferably performed indoors and combined with dust collection systems because of the high generation of dust. The collected dusts are often landfilled, even though they could hold the potential for recycling [31], hence opening a new research question. In this context, the quota of collected dust is considered landfilled and accounted for in the lost fraction of treated waste. The magnetic separation is considered to be performed by coupling two electromagnets to separate first ferromagnetic materials and then weakly-magnetic fractions. The electricity consumption is approximated from [32], considering an energy efficiency of the magnets of 80 %. The recycling route of recovered magnesia requires firing magnesia-carbon waste in a kiln to remove carbon. The treatment is assumed to be performed in a tunnel kiln at around 1400 °C, with natural gas consumption approximated from [33]. The CO_2 emissions are calculated stoichiometrically. Once the materials are crushed and purified, sieving is used to separate them into diverse size fractions. Each fraction is then packed in plastic bulk bags with a capacity of around 1.5 tonnes. Each bag is placed on a wooden pallet, respecting the safe load capacity of typical pallets of 1.5 tonnes. Regarding the transport modelling, the plant is considered to be located in France and sourcing spent refractories locally within a radius of 50 km. The waste to be disposed of is considered transported to the landfill by truck for 30 km.

The recycling rate quantifies the efficiency of the process in terms of quota, or mass, of treated waste effectively transformed into secondary materials. In this report, the efficiency is estimated from previous studies proposing values from real plants. Considering that only waste particles over 80 mm undergo manual sorting, 40 % of the input waste flow is considered unsorted [11]. The recycling processes determine the loss of an additional 15 % of the material as fine, resulting in 45 % of the initial waste stream converted into high-quality recovered magnesia-carbon and alumina. The recycling rate of recovered magnesia is even lower due to the oxidation of carbon during firing and its emission as CO_2. Assuming a carbon content of 10 %, the recycling efficiency is 40.5 %. The residual fraction composed of unsorted refractory waste and fine particles was demonstrated to contain the highest accumulation of impurities [14], probably due to the higher crushability of slag compared to refractories [34]. Yet, it holds potential for recycling. For instance, in the case of magnesia-carbon waste recycling, the residual fraction is commonly downcycled as a metallurgical additive in steelmaking. However, in this model, the fine fraction is considered to be landfilled, and the recycling rates only account for the production of high-quality secondary materials. Consequently, the LCA results presented here are expected to be higher than the real case and could be interpreted as a worst-case scenario for recovered magnesia and magnesia-carbon. The state-of-the-art recycling rates of alumina are harder to judge, given the lack of information in the literature. Despite the lower recycling rates, this LCA provides useful information on the magnitude of the expected environmental impacts and eco-design recommendations.

The inventories of the assessed product systems just described are shown in Table 1. The functional unit is 1 tonne of recovered material.

Table 1 - Life cycle inventory of recycled magnesia-carbon, magnesia and alumina. Benchmark case, FU: 1t recycled material.

	Unit	Recycled MgO-C	Recycled A	Recycled M
Refractory waste	kg	2.22E+03	2.22E+03	2.47E+03
Transport (input material)	tkm	1.11E+02	1.11E+02	1.23E+02
Electricity, low voltage	MJ	5.55E+01	5.67E+01	5.75E+01
Diesel	MJ	4.78E+00	4.78E+00	5.31E+00
Natural gas	MJ	0.00E+00	0.00E+00	4.30E+03
Lubricating oil	kg	5.25E-03	5.25E-03	5.83E-03
Polypropylene	kg	1.33E+00	1.33E+00	1.33E+00
Wooden pallet	unit	6.67E-02	6.67E-02	6.67E-02
Waste to landfill	kg	1.22E+03	1.22E+03	1.32E+03
Transport (waste to landfill)	tkm	3.67E+01	3.67E+01	3.96E+01
CO_2 (to air)	kg	0.00E+00	0.00E+00	5.43E+02
Particulate matter - tot (to air)	kg	1.35E+01	1.35E+01	1.50E+01
Recycled aggregates	t	1.00E+00	1.00E+00	1.00E+00

2.4.3. LCA results

The LCA characterisation results of MgO-C and A waste recycling are shown in Table 2. The LCA calculations have been made in LCA for Expert v. 10.9.0.31 using the EN 15804+A2 (EF3.1) impact assessment method. The results refer to the functional unit of 1 tonne of recycled material, namely magnesia-carbon (MgO-C), alumina (high-A) and magnesia (M).

Table 2 - Characterisation results of magnesia-carbon (MgO-C), high-alumina (high-A) and magnesia (M) waste recycling. EN15804+A2 (EF 3.1). FU: 1t recycled material.

Characterisation results, EN15804+A2 (EF 3.1). FU: 1t recycled material	MgO-C	High-A	M
Climate Change - total [kg CO_2 eq.][1]	45.59	45.66	918.29
Climate Change, fossil [kg CO_2 eq.]	45.31	45.37	917.87
Climate Change, biogenic [kg CO_2 eq.]Error! Bookmark not defined.	0.25	0.25	0.35
Climate Change, land use and land use change [kg CO_2 eq.]	0.04	0.04	0.07
Ozone depletion [kg CFC-11 eq.]	9.95E-07	9.97E-07	1.59E-05
Acidification [Mole of H+ eq.]	0.20	0.20	0.45
Eutrophication, freshwater [kg P eq.]	0.00	0.00	1.06E-02
Eutrophication, marine [kg N eq.]	0.07	0.07	0.16
Eutrophication, terrestrial [Mole of N eq.]	0.73	0.73	1.67
Photochemical ozone formation, human health [kg NMVOC eq.]	0.27	0.27	0.86
Resource use, mineral and metals [kg Sb eq.]	1.91E-04	1.94E-04	2.90E-04
Resource use, fossils [MJ]	987.15	996.93	5887.87
Water use [m^3 world equiv.]	15.53	15.63	25.10

The environmental performance of recycled magnesia-carbon and alumina aggregates is equivalent, with a negligible difference related to the slight variation in crushing electricity consumption. Instead, the environmental impacts of recycled magnesia are considerably higher due to the additional energy demand of the firing treatment. The most impacted environmental domains are determined by normalising and weighting the characterisation results. The normalisation entails comparing the characterisation results to a reference situation, while weighting requires multiplying the normalised results for a weighting factor that expresses the relative importance of each impact category to build the single score indicator. In the case of recovered MgO-C and high-alumina aggregates, particulate matter is the most impacted category, followed by the use of fossil resources, global warming potential and non-cancer human toxicity. The criticality hierarchy is similar in the case of recycled magnesia aggregates, even though particulate matter appears to be less impacted and not as critical as the other three categories. Once the critical environmental domains are identified, the interpretation of characterisation results indicates the environmental hotspots, i.e. the processes that generate most of the burdens. Hotspot analysis drives the identification of eco-design solutions by prioritising processes and materials for action. Figure 4 shows the average process contribution for recycled MgO-C (and high-alumina) and M, considering at first only the main environmental categories declared in EPDs and then all the environmental categories, including the optional ones. The second calculation is necessary to take into account those abovementioned critical categories that do not appear in the list of compulsory indicators, namely particulate matter and human toxicity.

[1] Total and biogenic climate change contain the emissions balancing the biogenic carbon in the packaging.

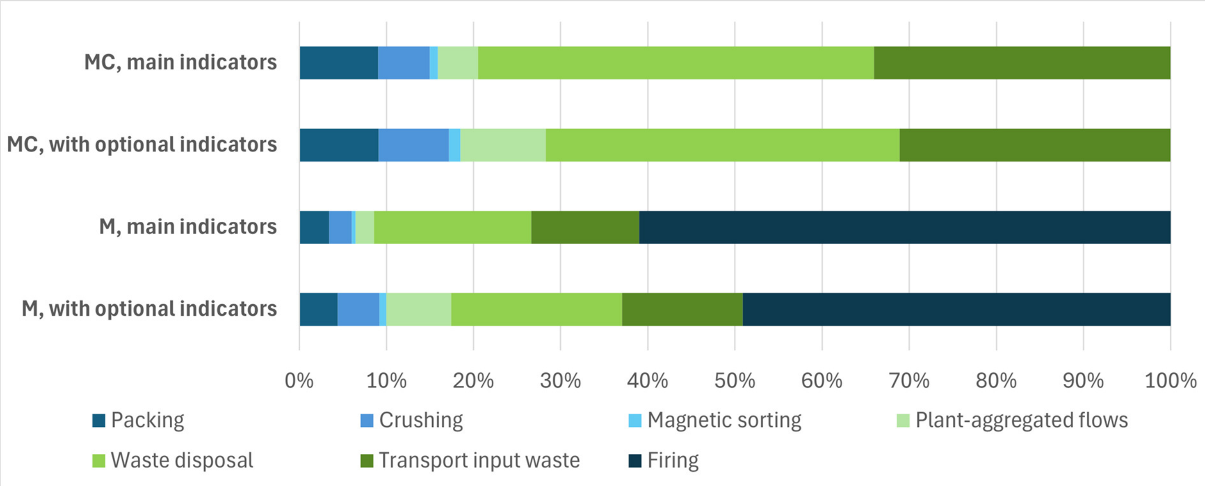

Figure 4 - Average process relative contribution in magnesia and magnesia-carbon recycling.

Considering the average contribution to the principal environmental domains, the transport and landfill of unrecovered waste are responsible for 45 % of the impacts of recycled MgO-C and A. The transport of recyclable waste from the steel plant to the recycling plant covers one third of the burdens (34 %) and the supply of packaging materials the 9 %. Instead, for recycled M, firing covers around 61 % of the total burdens, followed by the abovementioned final disposal of unused waste (18 %) and transport of input waste (12 %). When including the optional indicators in the analysis, a slight increase in the relative contribution of plant-aggregated burdens in MgO-C and high-A recycling is observed, with a combined decrease of waste disposal and input transport of 4 % and 3 %, respectively. The difference is higher in M recycling, where the increased relevance of plant-aggregated burdens, packing, and crushing generates a decrease of 12 % of the firing relative contribution. Neglectable contributions are generated by crushing and magnetic sorting. Focusing on the critical categories, the material handling on site (under the category "plant-aggregated flows") is responsible for 66 %, in magnesia, and 72 %, in magnesia-carbon and alumina, of the impacts on particulate matter. The other critical categories are mainly related to the transport of recyclable waste and the disposal of unrecovered waste, which jointly contribute to about 75 % of the impacts in MgO-C and high-A recycling. In the case of recycled magnesia, firing drives the use of fossil resources (82 %) and climate change (95 %), and it contributes to 45 % of human toxicity impacts.

The results interpretation must take into account the uncertainty of the approximated inventory values used in the assessment and their influence on the LCA results. Particular attention should be dedicated to the parameters that mostly influence the critical impact categories, namely the firing energy consumption, the transport distance of input waste and the dust emissions from material handling. In parallel, the description of the core recycling processes, i.e. crushing and magnetic sorting, requires further detailing to verify their minor contribution to the global environmental performance.

2.4.4. Sensitivity analysis, scenarios and eco-design recommendations

As described in the previous chapter, LCA results interpretation allows the identification of critical environmental categories and hotspots. Uncertainty, sensitivity and scenario analysis are tools that support a deeper characterisation and understanding of these results. An example of scenario analysis is presented in the current report, and other assessments are being performed within the CESAREF project. The transport of spent refractories to the recycling site is demonstrated to drive the burdens of recycled magnesia-carbon and alumina in the modelled system, despite the relatively short distance chosen. In the "transport scenario", the benchmark distance of 50 km is increased ten times (500 km) to account for the acquisition of waste from different countries across Europe. The scenario is not applied to the recycling of high-alumina refractories, given the almost equivalent environmental performance to recycled magnesia-carbon. The LCA characterisation results of the transport scenario are presented in

Table 3.

Table 3 - Characterisation results of "transport scenario" for recovered magnesia-carbon and magnesia. EN15804+A2 (EF3.1), FU: 1t recycled material.

Characterisation results, EN15804+A2 (EF 3.1). FU: 1t recycled material	MgO-C	M
Climate Change - total [kg CO_2 eq.][2]	234.15	1127.80
Climate Change, fossil [kg CO_2 eq.]	233.61	1127.09
Climate Change, biogenic [kg CO_2 eq.][2]	0.42	0.54
Climate Change, land use and land use change [kg CO_2 eq.]	0.13	0.17
Ozone depletion [kg CFC-11 eq.]	5.09E-06	2.04E-05
Acidification [Mole of H+ eq.]	0.81	1.13
Eutrophication, freshwater [kg P eq.]	0.02	0.03
Eutrophication, marine [kg N eq.]	0.28	0.39
Eutrophication, terrestrial [Mole of N eq.]	2.96	4.15
Photochemical ozone formation, human health [kg NMVOC eq.]	1.19	1.88
Resource use, mineral and metals [kg Sb eq.]	7.95E-04	9.62E-04
Resource use, fossils [MJ]	3683.55	8883.86
Water use [m^3 world equiv.]	31.87	43.25
Average variation on benchmark scenario	**+292 %**	**+92 %**

A relevant increase in all environmental categories in comparison to the benchmark case is observed. The average impact increase is 292 % in MgO-C recycling and 92 % in M recycling, which means that the generated burdens are 4 and 2 times those of the benchmark, respectively. Considering the process's relative contribution, transport becomes the main environmental hotspot in magnesia-carbon recycling, generating around 80 % of the total environmental impacts. In the case of magnesia recycling, transport becomes more critical than firing, being responsible for 51 % of the total burdens against 35 % of the heat treatment.

After analysing the results of the benchmark and scenario LCA, eco-design recommendations are proposed to reduce the environmental impacts of refractory recycling. Sustainability action plans should prioritise the reduction of environmental burdens on the most critical environmental domains, namely particulate matter, climate change, use of fossil resources and human toxicity. Solutions addressing the environmental hotspots are expected to be more efficient and generate bigger improvements. Hence, improvements should focus on the transport of spent refractories, the disposal of unrecovered waste, the firing and the on-site material handling. The scenario analysis demonstrates that the proximity of steel industries to the recycling plant is fundamental to guarantee low environmental burdens. When possible, refractory waste should be managed locally. When long distances can't be avoided, the most environmentally efficient transport mode should be chosen. For instance, full-load trucks with full return should be organised for road transport, or even better, railway transport should be favoured over the road. The impact of transport is proportional to the covered distance and the quantity of transported material. Thus, a higher recycling rate would reduce the transport's contribution to the total burdens due to the smaller quantity of spent refractory treated, and transported, to produce one tonne of secondary material. A similar impact reduction per tonne of

[2] Total and biogenic climate change contain the emissions balancing the biogenic carbon in the packaging.

recycled waste is expected at every treatment stage. In addition, the higher recycling efficiency translates into reduced impacts from unrecovered waste disposal, thanks to the lower quantity of landfilled waste. Solutions to improve manual sorting efficiency, such as the LIBS-based systems, could guarantee the reduction of the unsorted fraction and the increase of high-quality recycled materials production. In parallel, promoting the downcycling of the unsorted quota would further avoid landfill disposal. To reduce the impacts on particulate matter, the quantity of dust emissions should be reduced, for instance, by performing as many activities indoors as possible and installing dust collector systems. In the case of recycled magnesia, the firing energy efficiency is the key parameter driving most of the burdens. Energy efficiency could be improved by choosing the furnace with lower energy demand at the plant operating conditions, by carefully designing its operation to avoid energy waste, and by using green electricity and lower-impact fuels. Carbon capture systems could help reduce the impacts of climate change by capturing the carbon dioxide released by carbon removal. Table 4 synthesises the potential actions identified in this report to improve the environmental performance of refractory recycling. All the actions are to be tested through LCA to guarantee the avoidance of trade-off or rebound effects.

Table 4 - Eco-design suggestions for improving the environmental performance of refractory recycling.

Environmental hotspot	Key parameter	Potential action
Transport of spent refractories	Distance	Local waste management. For long distances, choose efficient transport modes.
	Mass of transported waste	Improve the recycling efficiency.
Waste disposal	Recycling rate	Improve the recycling rate: downcycle unsorted fraction; increase the efficiency of manual sorting.
Material handling and internal movement	Dust emissions	Indoor activities.
Firing	Energy consumption	Choice of the furnace and design of the operating conditions. Low-impact energy sources.
	CO_2 emissions	Carbon capture systems.

2.5. Potential benefits and loads from the use of secondary materials

2.5.1. Potential applications of secondary raw materials from refractory recycling

Recycled materials are believed to generate environmental benefits when substituting virgin materials. The statement was confirmed for refractories by the two LCA studies currently available in the literature assessing their recycling [7], [8]. Before quantifying the environmental performance of primary materials substitution, it is necessary to study the technical feasibility and the conditions for such replacement. This section summarizes the literature findings on potential applications for recycled magnesia, magnesia-carbon and high-alumina materials. The analysis focuses on the technical limitations and the optimal substitution ratio that ensures the recycled material can provide equivalent or similar performance compared to the primary material. The applications are listed in decreasing order of recycled material valorisation. In other words, at first, the replacement of high-quality materials in the refractory sector, either closed-loop or open-loop, is proposed. Then, downcycling options where recycled refractories substitute lower-quality materials are described.

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Many authors studied the closed-loop recycling of magnesia-carbon bricks [14], [35], [36] to reduce the consumption of virgin magnesia, usually in the form of sintered magnesia. In addition, the consumption of virgin carbon sources, mostly graphite, was also reduced, thanks to the carbon content of the recycled aggregates [3], [27], [36], [37]. The general trend in the literature seems to suggest avoiding real closed-loop recycling, preferring instead the use of recycled aggregates for lower-quality magnesia-carbon bricks. For example, aggregates containing fused magnesia are considered to replace primary sintered magnesia. Various studies suggested recipe adjustments by adding additives and binders to counterbalance the bad mechanical, corrosion and oxidation properties of recycled aggregates and guarantee good performance to the recycled refractory [14], [37]. Also, the design of the grain size distribution was demonstrated to be key for good refractory performance [3]. Overall, the recycled bricks demonstrated comparable properties to standard magnesia-carbon bricks in terms of lifetime, corrosion resistance and thermal conductivity [3], [35]. In some cases, the resistance to slag corrosion was even improved, with an overall reduction of refractory consumption in the steel ladle, due to the reduced maintenance by gunning [35]. However, their use was said to be limited to non-critical applications [8] and not appropriate in case of harsh conditions, such as those of the Basic Oxygen Furnaces (BOF) [36]. The optimal substitution ratio was indicated to be 20 % in [38], 30 % in [14], [39] with particularly positive effects from fines replacement, and 40 % in [3]. An alternative high-quality open-loop recycling option for spent MgO-C bricks is the use of recovered magnesia in carbon-free refractory products, such as gunning and ramming mixes [40], [41] or magnesia and magnesia-zirconia bricks [40], [42]. Only one study mentioned a maximum substitution ratio of 20 % in castables, over which the material properties decreased significantly [19]. In the case of magnesia bricks, relevant changes in the thermomechanical properties were observed with substitution ratios over 30 % [40]. However, the addition of zirconia strongly reduced such negative effects in magnesia-zirconia bricks [42]. Similarly to magnesia-carbon bricks, high-alumina spent refractories could provide secondary alumina for both shaped and unshaped refractories. Due to the lack of dedicated literature, it is assumed in this project that recovered alumina could substitute primary sintered alumina (or tabular alumina). By applying the same constraints of MgO-C recycling, a maximum substitution factor of 20-30 % is here assumed. However, this hypothesis finds, for the moment, no scientific validation and is considered valid only to calculate theoretical potential environmental benefits and burdens. Future research should focus on the technical feasibility of recycling high-alumina bricks.

When considering downcycling options, spent magnesia-carbon bricks substitute lime as metallurgical additives in steelmaking, while recycled alumina-silicate refractories commonly replace natural aggregates in concrete and road beds. The most relevant magnesia-based refractory downcycling consists of the replacement of doloma and dolomitic lime (dololime) in steelmaking as slag-forming agents. This open-loop recycling allows valorising a large fraction of fine waste that would otherwise be landfilled. Indeed, most of the fines are unsorted and not purified because they arrive at the recycling plant with a reduced size that is unsuitable for manual sorting [10]. Without further treatments, the accumulation of impurities and carbon [14] makes their recycling difficult, with the substitution of primary metallurgical additives being currently the only available recovery option. Slag is a foamy layer on top of the steel bath that collects the impurities from the molten steel, improves the energy efficiency of the furnace and protects the refractory lining. This practice is mostly used in Basic Oxygen Furnaces (BOF) and Electric Arc Furnaces (EAF). The slag composition is carefully designed and controlled by the use of metallurgical additives, such as metallurgical and dolomitic lime and doloma. The optimisation of the slag composition must take into account many factors, such as slag basicity, viscosity and magnesia saturation. A simplified approach for slag engineering in both EAF and BOF consists of prioritising its magnesia saturation [10], which is fundamental for both protecting the refractory lining and favouring the precipitation of secondary phases that serve as nucleation sites for the bubbles composing the foam. The action of the foaming agents is driven by their composition and dissolution rate. The literature disagrees on the dissolution properties of recycled MgO-C fines, as they were said to be comparable to standard slag conditioners in [43], while they were judged too limited in [44]. In the latter case, the problem was solved by the briquetting of recycled fines with bentonite binder, which resulted in their complete dissolution. Regarding the substitution ratio, the literature clarified that furnaces' operating conditions are too variable to suggest standard practices and that slag design should be specifically defined for every steel production campaign. For this reason, this report chose to adopt the substitution ratio described in [45] instead of making general, unreliable assumptions. In the study, full-scale trials in EAF demonstrated that the addition of 1 tonne per heat of spent magnesia-carbon would save 1.25 tonnes of traditional slag formers, i.e. a mix of dolomitic lime (~62 %) and metallurgical lime (~38 %). The higher quantity of magnesia introduced by the refractory compared to the standard fluxes increased the magnesia slag saturation, promoting a longer lifetime of the basic refractory lining. A reduction in the melting time and energy consumption was also observed [45]. Shifting the focus to recycled alumina, only one study referred to its possible use in steelmaking by replacing the calcium aluminate additives used in steel ladles promoting desulphurisation [34]. Indeed, the traditional calcium aluminate additive and calcium fluoride were completely replaced by the high-alumina recycled additive and lime, with the latter needed to guarantee the correct slag composition. However, the substitution ratio was not declared.

The second main refractory downcycling application consists of the replacement of natural aggregates in concrete. Due to their chemical composition, alumina-silicate refractories are promising substitutes for sand, gravel and clays in Portland cement-based concretes [46]. Their application was well documented in the literature. It was demonstrated that using recycled refractories increased the thermal resistance of concrete, especially for the optimal substitution ratio of 20 % and specifically adapted water-cement ratio [47]. Other studies mentioned increased high-temperature resistance in refractory-containing cement, but technical considerations were complicated by the lack of information on the refractory composition [48], [49]. The optimal substitution ratio of natural sand with refractory fines was 10-20 % in [49] and up to 20-40 % in [48]. In the case of concrete for paving blocks, the complete substitution of natural aggregates with recycled high-alumina (48 % alumina, 27 % silica) aggregates fulfilled the best technical and economic criteria [50]. Conversely, 100 % substitution was declared unfeasible in Portland cement [51]. Lastly, recovered alumina bricks from the glass industry were demonstrated to be a good substitute for silica fume in ultra-high-performance fiber-reinforced concrete [52].

In conclusion, the literature proposed various, sometimes conflicting, optimal substitution values for alumina-silicate refractories in concrete applications, based on the refractory composition, the type of concrete and the specific properties examined. It is worth mentioning that despite the potential for using recycled refractories in various concrete types, the common practice favours closed-loop recycling of construction and demolition waste into concrete. Nevertheless, in this context, it is believed that this application is worth addressing from an environmental point of view. The technical substitution limit is approximated to 20 % from the previous literature, even though further investigations are needed to verify the substitution feasibility when the alumina content in the refractory is around 80 %, as for the brick addressed in this study. Most of the observations on using recycled aggregates in concretes are valid for their application as roadbed material in road construction, which is defined as one of the most widespread downcycling options for recovered refractories [1], [19]. Similarly to construction and demolition waste, recycled refractory aggregates and fines could replace natural sand and gravel as raw materials for structural layers of unconsolidated roads [46], [53], [54]. The addition of 5 % recycled alumina (65 % purity) was demonstrated to improve the mechanical behaviour of the road, but further analysis is needed to calculate the optimal addition value to avoid unwanted effects such as greater swelling [55]. The literature suggests that alumina should preferably cover the finer fraction; hence, in this report, a 1:1 substitution of natural sand with secondary alumina fines is considered. Lastly, a less-known recycling option for magnesia-based refractories is their use in magnesium fertilizers [9], where they could substitute primary calcined magnesia, which is the most concentrated form of magnesium [56]. Such a substitution is only feasible for those recycled materials with similar properties to calcined magnesia, yet knowing that most of the spent refractories are recycled into sintered magnesia. However, the consumption of this type of fertiliser is usually low because of the high concentration and the slow release of magnesium into the soil. This application poses technical challenges, given that the elimination of all possible toxic contaminants is required.

In addition to their technical and environmental relevance, recycling practices potentially generate economic benefits. The value of recycled refractories is limited to the cost of the replaced materials, hence, closed-loop recycling can potentially generate higher economic benefits than open-loop options [1]. The price of recycled refractory raw materials can vary in the range of 60-100 % of the respective primary materials [5].

2.5.2. Analysis of the environmental performance

Once the raw material substitution is demonstrated as technically feasible, LCA can calculate the associated effects on the environment by comparing the impacts of the targeted primary and secondary materials. In cradle-to-cradle LCAs, this comparison can be used to attribute environmental credits to the product generating the recyclable waste. In the EPD of construction materials, the potential benefits and loads are calculated in cradle-to-cradle assessments but declared separately, hence providing no credit to the original product. Instead, in EPDs of secondary materials based on cradle-to-gate LCAs targeting only the recycling treatments, as described in section 2.4, no potential benefit is calculated for the recycled material.

Without taking into account environmental declarations and credits, the current section describes the theoretical background for calculating the potential benefits and loads from raw materials substitution. The LCA of MgO-C and high-alumina recycling studied in this report will be soon performed, under the EN 15804+A2 framework, within the PhD02 project. Equation 1 describes the potential environmental benefits and loads when substituting 1 tonne of virgin materials.

$$I_s = I_p - I_r * m_r * q \qquad \text{Equation 1}$$

I_s: potential benefits and loads per 1 tonne of substituted material

I_p: impacts from the production of 1 tonne of primary material

I_r: impacts from the production of 1 tonne of recycled material

m_r: mass of recycled material required to substitute 1 tonne of primary material

q: quality factor

When applying the formula, positive results represent avoided burdens, or environmental benefits, while negative values represent additional environmental impacts (loads). The equation compares the environmental impacts of the targeted primary and secondary material production, at the point of functional equivalence. This means that the secondary material is considered to enter a certain product system substituting the primary material at the point where it can provide the same function of the substituted material. The impacts arising from the production of the primary material account for all life stages from raw material extraction (cradle) to the point of functional equivalence. Instead, the impacts generated by the production of the recycled material are calculated from the point of end-of-waste state to the point of substitution. As shown in Equation 1, the impacts per tonne of recycled material are multiplied for the quantity of material required to substitute one tonne of primary material. Indeed, due to the different properties of the two materials, a different mass could be required to perform the addressed function. If the functional equivalence can't be reached, a quality factor is applied. The value-correction factor is calculated as the ratio between the quality of the secondary and substituted material. The point of functional equivalence can vary for a secondary material based on its application. In all cases, however, it is considered to be reached at the consumer plant, hence, the transport of primary and secondary materials is included in the respective systems. The use of secondary materials could change the geography of the supply chain by replacing non-European materials with recycled aggregates produced in Europe, hence further reducing the environmental impacts due to the lower transport contribution. This could be the case with magnesia, which is currently mostly produced in, and hence sourced from, China. When recycled aggregates require additional on-site treatments that are not performed on virgin materials, such as crushing or drying, the substitution point is reached after the treatments. Any change in the manufacturing process of the product containing the primary material, caused by the replacement with a secondary material, is to be addressed through the quality factor. In case of extensive changes, it could be considered that the recycled content generates a completely new production route, hence, it could be argued that the functional equivalence is not reached, even in case of improved performance.

Table 5 presents an example of technical information to be collected to calculate the potential benefits and loads from raw material substitution. The values refer to the applications of recycled magnesia-carbon described in section 2.5.1. First, the type and quantity of substituted raw materials have to be specified in order to calculate a substitution factor. In the case of MgO-C bricks closed-loop recycling, primary sintered magnesia (or Dead Burnt Magnesia - DBM) and carbon, in the form of graphite, are replaced. Considering 10 % of carbon in recycled MgO-C, 1 kg of aggregates is considered to replace 0.9 kg of DBM and 0,1 kg of graphite. Indeed, it is considered a 1:1 replacement factor between carbon and graphite and between the non-carbon quota of the aggregates and virgin magnesia. The literature demonstrated that the functional equivalence of recycled magnesia-carbon was guaranteed with a substitution ratio lower than 30 %. Such technical limitation must be declared together with the substitution factor and eventual LCA results. In the case of metallurgical additive substitution, the different composition of primary and secondary materials makes the calculation of the replacement factor more complicated, as demonstrated in section 2.5.1. In this case, the factor 1:1.25 proposed in [45] is considered for the substitution of dolomitic and metallurgical lime with recycled magnesia-carbon fines. Regarding the contribution of transport to the environmental burdens, the origin, transport distance and mode are to be declared for all primary and substituted materials. Virgin magnesia is assumed to be sourced in China, arriving in Europe by sea transport (around 16000-17000 km) and reaching the consumer plant by truck (100-500 km). Recycled aggregates are considered to be transported only by truck within Europe (100-500 km), hence, they are expected to have lower transport-related environmental impacts. Similar to recycled materials, dolomitic and metallurgical lime are considered to be produced in Europe, hence "locally" sourced. The exact distances covered by the materials depend on case-specific considerations.

Table 5 - Synthesis of parameters and technical limitations for the calculation of potential benefits and loads from the substitution of primary materials with recycled magnesia-carbon.

Recycled material	Substituted material & application	Substitution factor per kg of recycled material	Technical limitations	Origin of virgin material
MgO-C aggregates	DBM magnesia and graphite in MgO-C bricks	0.9 kg DBM + 0,1 kg graphite	30 % maximum substitution ratio	China
MgO-C fines	Slag formers in steelmaking	1.25 kg additive (38 % metallurgical lime, 62 % dolomitic lime)	Slag design specific to the steel production campaign	Europe
Magnesia fines and aggregates	DBM magnesia in gunning and repair mix, M and MZ bricks[3]	1 kg DBM	30 % maximum substitution ratio	China

3. Conclusions and next steps

The interest in refractory recycling is constantly growing due to the normative requirements pushing towards sustainability and the potential economic benefits of producing recycled materials. However, only two studies in the current literature quantify the environmental performance of recycling through life cycle assessment. The study presented in this report covers many research gaps in order to set a solid base for improved LCAs and guide future research by listing the most challenging and relevant topics to be addressed next.

First, the study combines the LCA environmental assessment with a detailed description of state-of-the-art recycling practices relying on technical information. Such a combination is unprecedented, as previous studies only focused on the recycling technical feasibility or the calculation of the environmental burdens. The process-level assessment of the environmental performance guarantees a better interpretation of the LCA results and simplifies the proposition of more accurate eco-design recommendations. The recycling of spent magnesia-carbon and high-alumina refractories is used as an example in the current study. A deeper level of detail is provided for spent magnesia-carbon refractories, thanks to the larger literature describing the many available treatment options. Instead, more general considerations and approximations are provided for high-alumina refractory recycling with 80 % alumina content. A significant research gap remains regarding the technical feasibility of alumina recycling and the potential application of the recovered materials. From a larger perspective, adapted process flowcharts and operating parameters should be detailed for the most relevant spent refractory categories. Such a goal is achievable on one side, by verifying the treatments' feasibility and efficiency at the laboratory level, and on the other side, by collecting information and primary data directly at recycling plants. The low data availability and quality are currently some of the biggest criticalities to performing high-quality assessments. Hence, it is essential to enlarge the dataset coverage to other materials, recycling techniques and geographies.

Besides detailing the recycling treatments, the study proposes a methodological framework to face the main modelling challenges identified for the LCA of recycling. The cut-off plus credit methodology is applied in this context because of its capacity to show the potential benefits and loads from using recycled materials, still addressing the recycling treatments from an attributional

[3] M, magnesia. MZ, magnesia-zirconia

perspective. In addition, the approach should facilitate the communication, understanding and application of LCA for companies and non-experts, given its wide application in various industrial sectors to create environmental declarations (EPD). However, the best modelling approach should be further studied by applying other methodologies to evaluate the influence of the allocation approach and the impact assessment methodology on the LCA results.

Regarding the environmental performance of refractory recycling, the LCAs performed in this study attribute most of the environmental impacts to the transport of spent refractory to the recycling plant, the landfill disposal of the unrecovered waste and, when appropriate, the energy consumption of heat treatments. A short supply chain and high recycling rates are promising solutions to reduce the environmental burdens of recycled materials. Further analyses are ongoing in CESAREF to verify the environmental performance of such sustainable actions, as well as to calculate the potential benefits and loads from the substitution of virgin materials.

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