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LCA OF WASTE MANAGEMENT SYSTEMS

Ex-ante life cycle assessment of FineFuture flotation technology: case study of Grecian Magnesite

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Abstract

Purpose This study aims at evaluating the environmental performance of a novel froth flotation technology in mining industry from a life cycle perspective. The technology is being developed under EU Horizon 2020 project titled "FineFuture" (FF) with the aim of saving valuable materials in fine particles that are currently wasted due to lack of technology.

Methods FF relies on chemically enhancing the physical characteristics of particles allowing it to float and concentrate. Prospective life cycle assessment (pLCA) was conducted for two possible industrial applications of FF flotation technology in the case study of Grecian Magnesite (GM) which is a main magnesium oxide producer in Europe. Each application can be perceived as a standalone comparative LCA study comparing current system with future system incorporating FF technology on industrial scale.

Results and discussion The future scenarios did not decisively support FF technology in neither of the two applications from an environmental point of view. When applied to fines of <4 mm granular size with the aim of material recovery, the future scenario performed better than the current situation only in 5 out of 16 impact categories. The main issue is the added burden of calcination phase. When the technology was tested to upgrade the existing magnesite concentrate before calcination, it introduced some gains in most of the impact categories, but the difference compared to the current situation is not very considerable. Testing improved scenarios showed a great benefit to the overall performance of the scenarios by introducing cleaner fuels and burners in calcination phase.

Conclusion and recommendations Overall, the results tend to favour applying FF technology to upgrade low quality concentrates rather than beneficiating <4 mm fines. However, and in any case, if FF technology is to be applied, combining it with cleaner fuels and burners in calcination should be prioritized. Furthermore, it was found that improving the purity (i.e. quality) in the flotation tank output is a key factor from an environmental view. The results also showed little impact of the added electric energy demand from the new units. As any pLCA, the study has limitations mainly originating from the low technology readiness level (TRL) when data collection activities were carried out. Further studies should start from pilot-scale data and adopting more accurate upscaling approaches to calculate the impacts of a full industrial deployment of the technology.

Keywords Prospective life cycle assessment · Froth flotation · Emerging technology · Raw material conservation · Mining industry · Minerals recovery

1 Introduction

Using Life Cycle Assessment (LCA) methodology to evaluate the environmental performance of emerging technologies has become a common practice nowadays. With the increased research in this particular use of the methodology, a new branch of LCA studies emerged under the name "prospective" or "ex-ante" LCA among other names to distinguish traditional LCA that is applied to existing mature systems from LCA applied to new technologies that are still under development (Bergerson et al. 2020; Cucurachi et al. 2018; Moni et al. 2020).

In this study, prospective LCA was applied to evaluate the environmental performance of a novel froth flotation technology in the mining industry. Froth flotation is a physicochemical separation technique that utilizes the variation in the surface wettability of mineral particles. From

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a heterogeneous mixture of solids, hydrophobic particles are made to attach to gas bubbles then they are carried to the froth phase and recovered as a froth product (typically the value mineral concentrate), while hydrophilic particles remain in the pulp phase and discharged as tailings (Wang and Liu 2021). However, no current froth flotation technology can efficiently deal with ultra fine particles and therefore there is a need for new ground-breaking technologies to tackle this limitation. The new technology was developed under FineFuture (FF) EU HORIZON 2020 project with the ultimate goal of recovering valuable materials from very fine mineral particles which are currently lost as tailing deposits or as fine-grained mineral by-products due to lack of adequate technology to process them. Despite the foreseen environmental benefits, a holistic evaluation is of utmost importance to avoid environmental burden shifting.

As far as the authors' knowledge, no or very few previous pLCA case studies were provided for the mining sector and on a specific mineral beneficiation principle like froth flotation, hence this study opens new research doors in a very important sector especially with the raw materials scarcity that the entire world is facing nowadays. Beneficiation is a technical term used in mining sector and it means mineral processing or ore dressing.

This research gap is emphasized by Marmiroli et al. (2022) in their systematic literature review on LCA in minerals and beneficiation systems which concluded that flotation process and more generally beneficiation stage is typically overlooked in traditional LCA literature with flotation being rarely investigated as a stand-alone process in the system. According to the authors, the reason could be that beneficiation is a very material and site-specific stage, which makes it challenging to draw parallelism amongst the same processes applied to different sites. All this adversely affects the transparency of the inventory of the production of many products in the sector which we try to tackle here.

The work carried out in this study consists of two standalone comparative LCAs: each LCA represents a different implementation of the new technology in the current production line of Grecian Magnesite (GM), one of the industrial partners in FF project consortium. Furthermore, the study explores various technological scenarios and modelling choices.

2 Materials and methods

GM is a leading Greek company in magnesia (magnesium oxide) production. The company is operating on the magnesite reserves in Yerakini Mines and Works in Chalkidiki, Greece. Magnesia is the final product of thermal decomposition of magnesite (magnesium carbonate), and it comes in three types: Caustic calcinated magnesia (CCM), Sintered or Dead burnt magnesia (DBM), and Fused magnesia. GM produces the first two types of magnesia. Figure 1 shows a simplified version of GM current production line with beneficiation phase in its core. The system is described in more detail in Eltohamy et al. (2022).

The intensive washing of magnesite ore that takes place in the beneficiation phase generates fine particles of granular size < 4 mm which is currently discarded and stockpiled (Flow number 1) despite the high mineral concentration this fraction contains. This fraction is one of the targeted flows of GM to be beneficiated with FF flotation technology which can allow obtaining good quality magnesite concentrate for calcination in the future. Another suggested application by GM is to apply the FF technology to currently beneficiated magnesite concentrate with $MgCO_3$ concentration below 91% (Flow number 2) aiming at providing higher-quality feed to calcination kilns.

Due to this application uncertainty, two cases for the two applications were developed each representing a separate comparative LCA since each application implies different modelling choices like what units to include in the system boundary and how the functional unit will be defined. The future flotation plant is depicted in the blue box in Fig. 1.

2.1 Goal and scope

The goal of the study is defined for each case of the two cases explained previously as follows:

- Case 1: considering the flow of < 4 mm fines, to compare the potential environmental impacts of their discarding in stockpiles vs those of their beneficiation with FF flotation technology;
- Case 2: to compare the potential environmental impacts of current $MgCO_3$ calcination vs those associated with the upgrading of low quality $MgCO_3$ concentrate before calcination.

2.1.1 System boundary

Figure 2 and Fig. 3 show the system boundary in case 1 including inputs and outputs of each unit process in terms of material and energy. In Fig. 2, the LCA system is composed of the transportation of discarded fines of granular size < 4 mm with lorry, in addition to stockpiling. On the other hand, Fig. 3 shows the main unit processes in the future, starting from the milling of the fines (necessary to feed the flotation unit) until the magnesia production. Stockpiling exists here as well in the beginning of the line but, in this case, it is a temporary buffer stocking just before feeding the mill. In the calcination department, there is the stocking area from which the kiln feed is

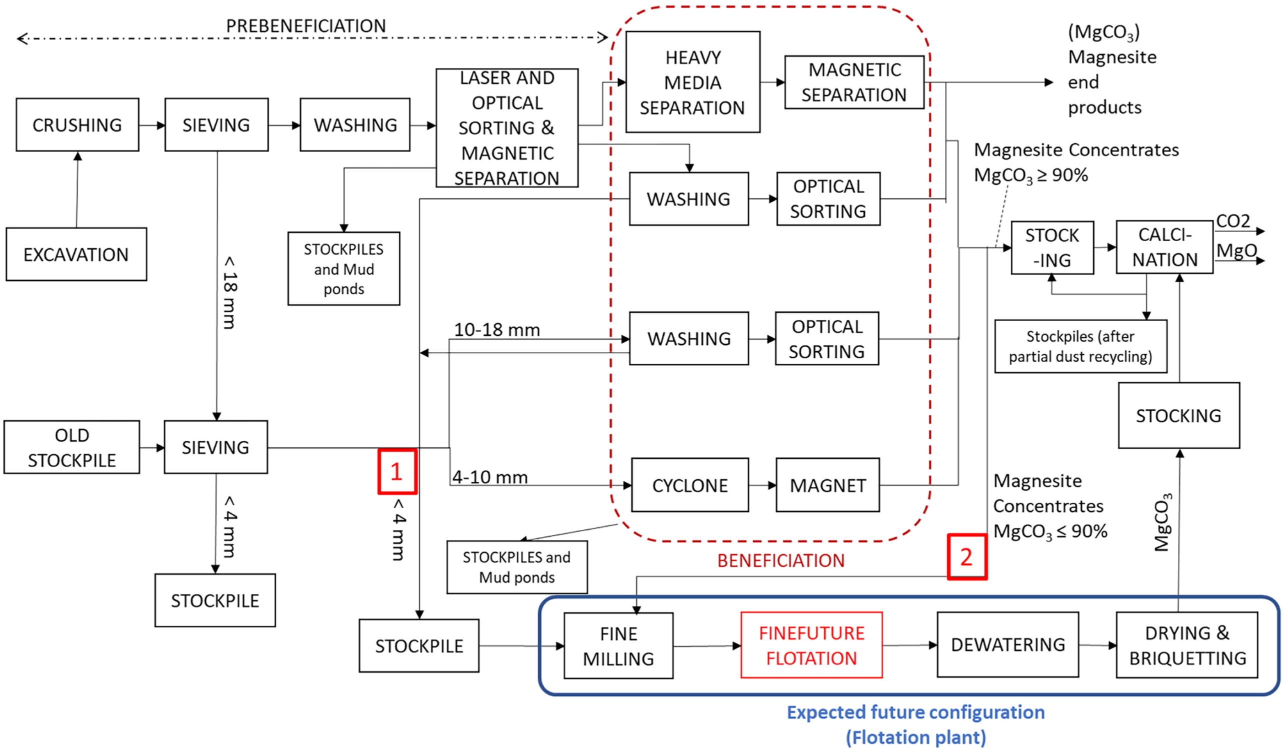


Fig. 1 Grecian Magnesite production line

transported with a loader to be fed to the kilns, then lastly the flue gas treatment units. The flue gas abatement is composed of desulfurization unit in which calcium hydroxide is used, in addition to electrostatic precipitators and bag filters for dust removal. Part of this dust is recirculated to enter the kilns again, and part goes to permanent stockpiling.

Case 2 is represented in Fig. 4 and Fig. 5 for present and future respectively. The present system includes only the

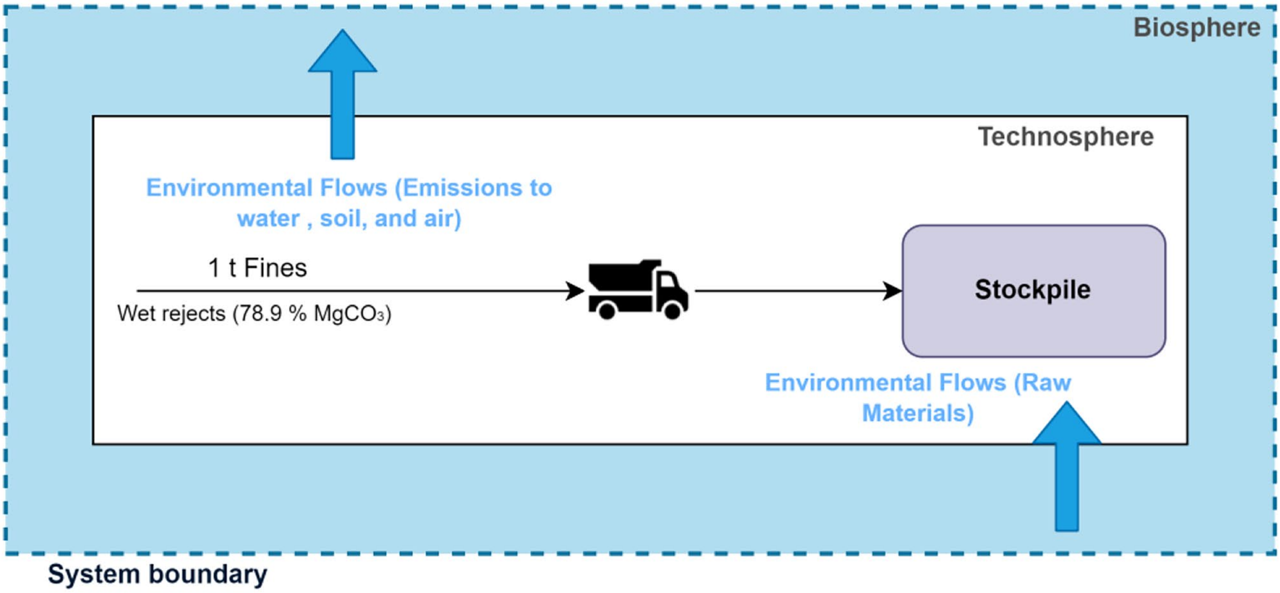


Fig. 2 GM case 1: system boundary (present)

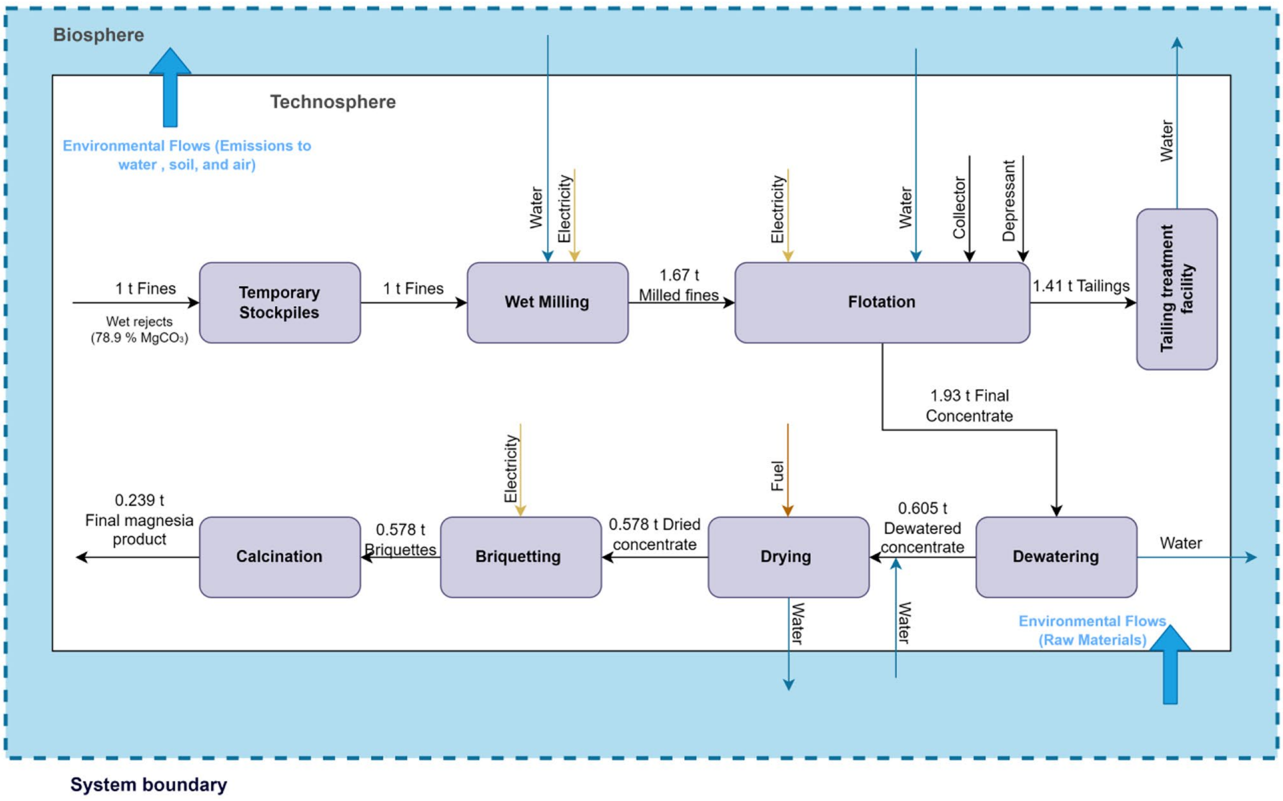


Fig. 3 GM case 1: system boundary (future)

transportation of beneficiated magnesite concentrate from the beneficiation department to the calcination square and the calcination department. In the future, there are two distinguishable flows based on the quality of the magnesite coming from beneficiation. The flow with relatively lower quality is directed to FF route to be furtherly concentrated before calcination, while the rest goes directly to calcination.

All the transportation between the different unit processes is accounted for in the model even if it not shown explicitly on the flow charts for simplification purposes. Moreover, the tailings treatment facility is shown as one block, however in reality it is composed of a dewatering unit and a tailing pond.

It was not necessary to include any other parts from the main GM plant other than the unit processes shown in the systems boundaries here given the comparative nature of the LCA.

2.1.2 Functional unit and multifunctionality

The functional unit (F.U.) for case 1 is *the treatment of 1 tonne of discarded fines of granular size of* <4 *mm*. A similar functional unit was considered for case 2: *the treatment of 1 tonne of beneficiated magnesite concentrate coming from beneficiation stage*. A different functional unit based on the produced magnesia could not be defined in case 2 because the final product is not identical. Indeed, the quality of the output product in the future case 2 will be higher than current quality thanks to FF upgrade: this implies that the downstream market of the magnesia produced now and of the one produced in the future scenario will be different, as stated by GM.

Since treatment of input was defined as the system function in both cases, a multifunctionality problem emerges in the future scenarios of both cases due to the additional function of magnesia production. To address multifunctionality, substitution by system expansion (Hauschild et al. 2018; ISO 2020) was adopted in both cases taking into account the avoided environmental impacts of primary production of magnesia through a conventional route. Impacts associated with average primary production of magnesia in Europe was taken from ecoinvent 3.8 database. A key challenge in this case was defining the substitution ratio (Rigamonti et al. 2020). Ecoinvent dataset on Magnesia production hypothetically assumes 100% pure MgO product. The substitution ratio had to account for quality variations, so the substitution ratio was taken as the purity of the produced magnesia from future systems.

Moreover, the substituted ecoinvent dataset was found to contain certain issues related to energy modelling. These

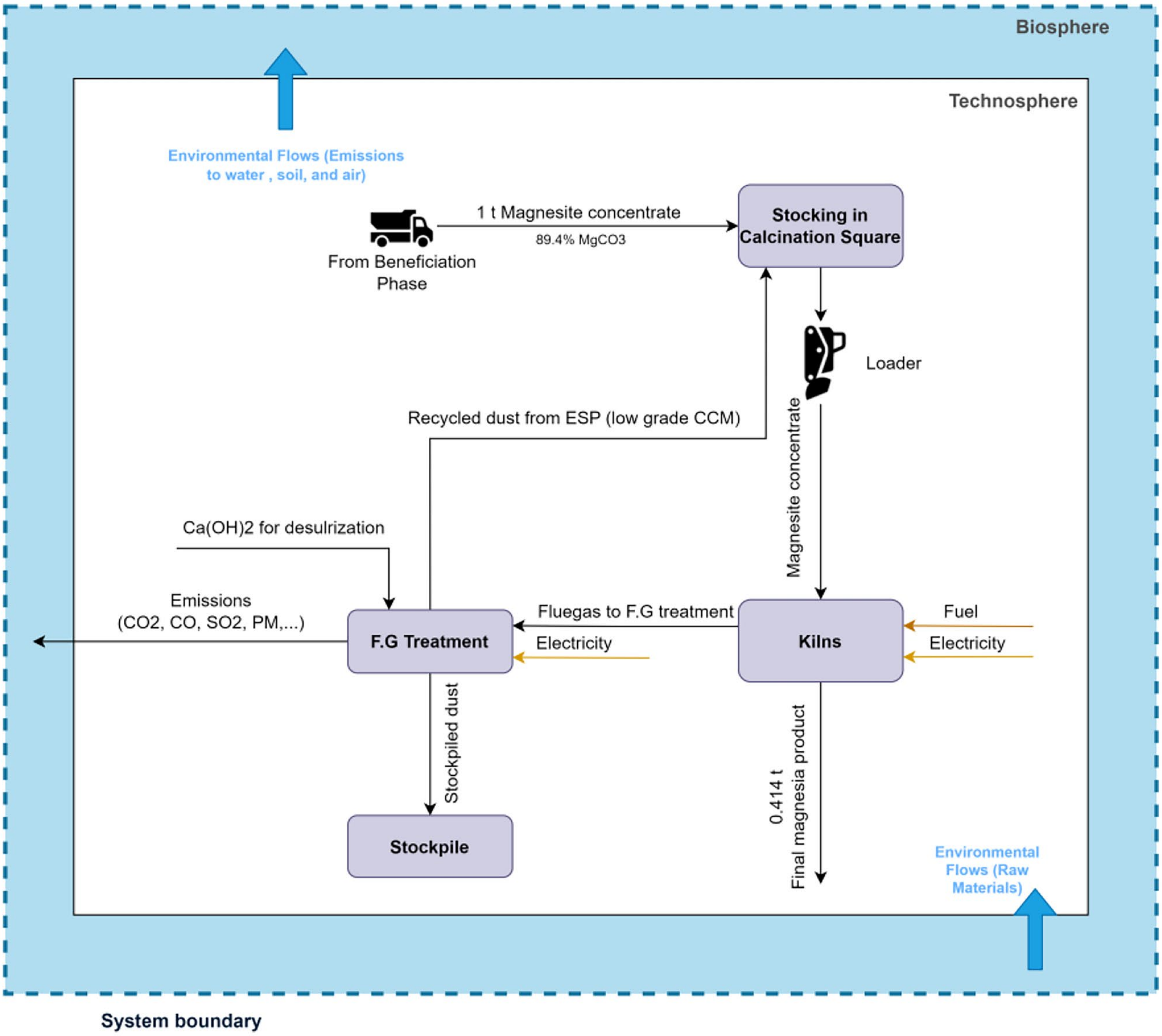


Fig. 4 GM case 2: system boundary (present)

issues were communicated to ecoinvent who promised corrections in next updates, but in order to complete the study, the dataset was manually adjusted as far as possible using Schorcht et al. (2013). Even with that, scepticism regarding the dataset quality was still an issue. Thus, physical allocation based on mass property was also tested in case 1 to verify the results of substitution. Applying allocation to such systems (i.e. waste management systems) is not a common practice in LCA literature and therefore a new allocation approach is proposed in this article (See Sect. 1 in supplementary materials). The underlying principle of this new approach is assigning allocation factors to unit processes based on the degree of involvement in fulfilling each function considering some technical assumptions. It was assumed that the function of waste treatment of fines ends when the material achieves the End-of-Waste (EoW) state (European Council 2008) which practically occurs after drying because once dried, the concentrate coming from FF is already a high-quality magnesite concentrate that cannot be labelled as waste anymore. The two following phases of briquetting and calcination however are only necessary to produce magnesia. Therefore, the inventory of briquetting and calcination were entirely allocated to the secondary function (i.e. production of magnesia) while upstream unit processes are only partially allocated to it. Pure magnesite content mass was utilized to calculate the allocation factors: this led to allocating only 40% of unit processes preceding briquetting to magnesia production function.

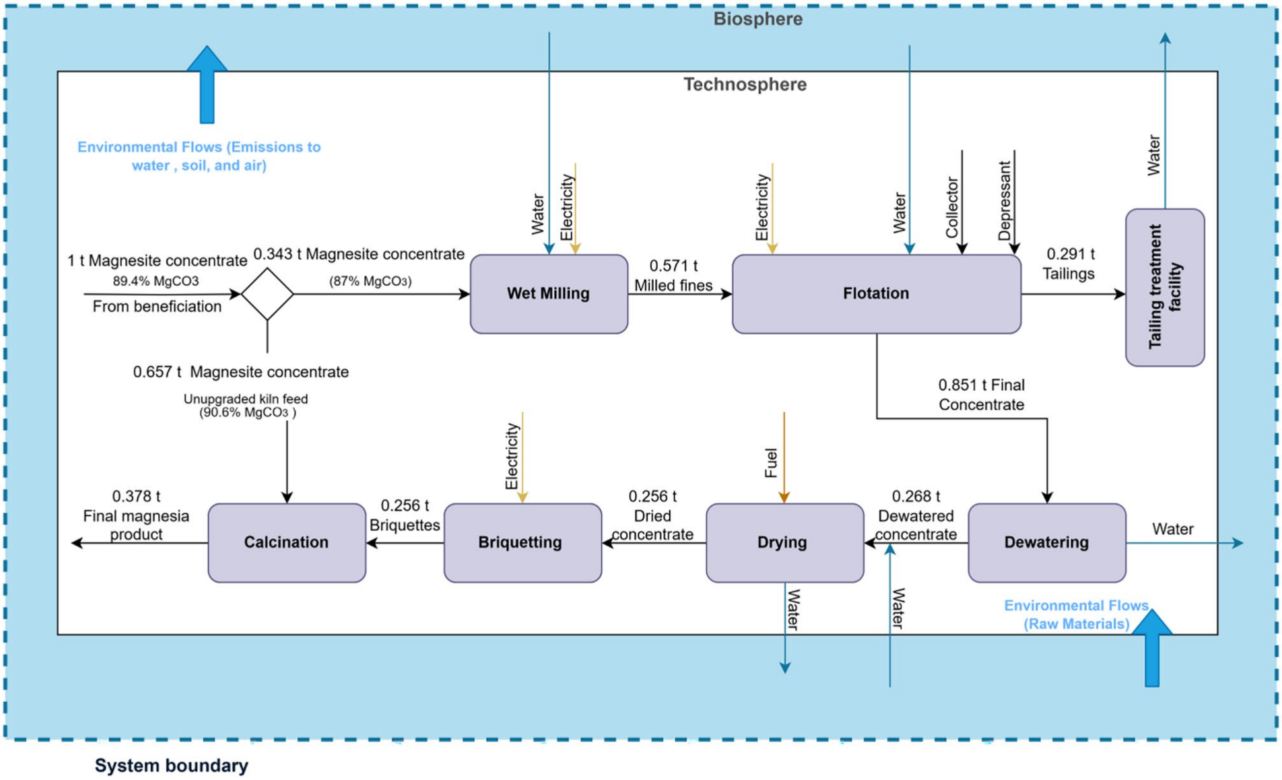


Fig. 5 GM case 2: system boundary (future)

2.1.3 Upscaling

The upscaling of the technology from lab-scale or pilot tests to industrial scale is one of prospective LCA major challenges (Moni et al. 2020). In this study, the upscaling framework proposed by Tsoy et al. (2020) was taken as a reference in which the first step is projected technology scenario definition. The result of this step is the flow chart of the main system of GM and future possible FF applications in Fig. 1. Second, a preparation of a projected LCA flowchart is done converting expected new installations into unit processes, in addition to defining function, functional unit, reference flow, system boundaries, etc. The outcome of this step can be seen in Figs. 2, 3, 4 and 5 complemented by the description provided here under goal and scope definition (e.g. Functional Unit). Last step is the data estimation to complete the flowchart of step two. There are different ways to do that according to Tsoy et al. (2020) from which "manual calculations" on available primary data was the main approach utilized supported with minor use of proxy data (e.g. data on components of collector and depressant chemicals). This was done in close coordination with technology experts who are working in FF project and GM research and development department. Linear upscaling was also used at many parts when no other information was available (e.g. electricity consumption in briquetting). Linearity assumption does not consider the economy of scale and improvement of efficiency thanks to upscaling in production lines. This can eventually result in overestimations of some flows and hence some environmental impacts.

2.1.4 Scenarios definition

In addition to the cases 1 and 2 defined above which concerns how the technology will be deployed on a full industrial scale, another type of scenarios was given the name "sub-scenarios". These sub-scenarios represent expected future changes in the main system but not directly related to the new flotation unit, yet these changes like change of materials, fuels or infrastructure can have crucial impact on the overall environmental performance. The importance of changes in background systems is stressed on in literature of prospective LCA (for example, Gibon et al. 2015; Mendoza Beltran et al. 2020; Sacchi et al. 2022; Schropp et al. 2022). The defined cases and sub-scenarios in the present and future are illustrated in Table 1. The technology choices that defined the sub-scenarios originated from the preliminary results obtained where the fuel and emissions in calcination were found very impactful. Furthermore, these modifications in fuels and kilns are actual plans by GM that are currently tested to be executed in the near future.

Table 1 Scenarios definition

Case	Present		Future	
	Scenario code	**Description**	**Scenario code**	**Description**
Case 1	S1.0	Stockpiling	S1.1	FF technology + Business-as-usual (BAU) calcination with fossil dominated fuel mix and conventional kilns
			S1.2	FF technology + New fuel mix in kilns (50% energy replacement by biomass)
			S1.3	FF technology + New fuel mix in kilns (50% energy replacement by biomass) + New low NOx emitting burners (kilns)
Case 2	S2.0	Business-as-usual (BAU) calcination with fossil dominated fuel mix and conventional kilns	S2.1	FF technology + Business-as-usual (BAU) calcination with fossil dominated fuel mix and conventional kilns
			S2.2	FF technology + New fuel mix in kilns (50% energy replacement by biomass)
			S2.3	FF technology + New fuel mix in kilns (50% energy replacement by biomass) + New low NOx emitting burners (kilns)

2.2 Inventory

Tables 2 and 3 show the inventory for S1.0 and S1.1 respectively together with the details of the modelling. A separate inventory for calcination department is provided in Tables 4 and 5 for S1.1.

The inventories for S2.0 and S2.1 are provided in a similar manner in Tables 6, 7, 8, 9 and 10. Infrastructure works like construction and dismantling were excluded from the scope of the study.

Data on material and energy consumption, and emissions of calcination was provided directly by GM. Moreover, GM also provided the following empirical equation to estimate the magnesia (MgO) concentration in the kiln output (i.e. final product quality) having kiln-feed quality as input to the equation:

$$\%MgO = \frac{\%MgCO3}{\%MgCO3 + (100 - \%MgCO3) \bullet 2.092}$$

In S1 scenarios, it is estimated that starting from 78.9%wt $MgCO_3$ in the fines, $MgCO_3$ concentration can increase to 90%wt thanks to the new FF flotation unit. By applying that into the equation above, the percentage of MgO in calcination output is expected to be around 81%wt which was used as substitution ratio as explained previously in Sect. 2.1.2. In S2 scenarios on the other hand, the high-quality magnesite with a concentration higher than 91%wt are excluded from FF upgrade and will go directly to calcination. The remaining part is divided into two halves each contains around 87%wt of $MgCO_3$ on average. According to GM, one half goes directly to calcination with the high-quality concentrate (i.e. > 91%), while the other half will go through the upgrade line of FF. So eventually, the blend that goes directly to calcination has a weighted average of 90.6%wt $MgCO_3$, then it is assumed that it will be mixed with the output briquettes of FF line which will raise the overall concentration of the kiln feed to 92.4%wt $MgCO_3$ on average. By applying the empirical equation, this will result in a final magnesia product of approximately 85.35%wt purity (i.e. substitution ratio in case 2).

The new fuel mix in S1.2 and S2.2 is a result of substituting petcoke with a new blend of biomass and petcoke. Each tonne of petcoke removed will need to be replaced by around 1.5 tonne of blend due to the relatively lower energy content of biomass. The ratio between biomass and petcoke in the new blend is 2:1 on mass basis respectively where biomass in the new

Table 2 Inventory of S1.0 referred to the functional unit

Unit process		Flow	Amount	Unit	Ecoinvent dataset/Note
Stockpiling	**Input**	Transportation	0.4	tkm	Transport, freight, lorry 16–32 metric ton, EURO3 {RER}| transport, freight, lorry 16–32 metric ton, EURO3 | Cut-off, U (From beneficiation to stockpiling)
	Output	Inert landfilling (< 4 mm fines)	1	t	Inert waste, for final disposal {CH}| treatment of inert waste, inert material landfill | Cut-off, U

Table 3 Inventory of S1.1 referred to the functional unit

Unit process		Flow	Amount	Unit	Ecoinvent dataset/Note
Temporary stockpiling	**Input**	Transportation[a]	0.4	tkm	Transport, freight, lorry 16–32 metric ton, EURO3 {RER}| transport, freight, lorry 16–32 metric ton, EURO3 | Cut-off, U (From beneficiation to stockpiling)
	Output	Transported fines	1	t	Going to wet milling
Wet milling and pumping	**Input**	Transportation	0.5	tkm	Transport, freight, lorry 16–32 metric ton, EURO3 {RER}| transport, freight, lorry 16–32 metric ton, EURO3 | Cut-off, U (From stockpiling to wet milling)
		Water[b]	0.67	m^3	Input from nature (Water, unspecified natural origin, GR)
		Electric energy	10.8	MJ	Electricity, low voltage {GR}| market for | Cut-off, U
	Output	Milled < 4 mm fines	1.67	t	Going to FF flotation plant
FF flotation plant (incl. cleaner and scavenger)	**Input**	Collector (Resanol)	500	g	See Sect. 2 in supplementary materials
		Depressant (Sodium Hexametaphosphate)	200	g	Sodium tripolyphosphate {GLO}| market for | Cut-off, U (See Sect. 2 in supplementary materials)
		Water	1.67	m^3	Input from nature (Water, unspecified natural origin, GR)
		Electric energy	3.6	MJ	Electricity, low voltage {GR}| market for | Cut-off, U
	Output	Final concentrate	1.93	t	Going to dewatering of final concentrate
		Tailing to dewatering	1.41	t	Going to dewatering of tailing (Sect. 3 in supplementary materials)
Dewatering of final concentrate (Thickener (Derrick screens)/ filtration)	**Input**	Electric energy	0.991	MJ	Electricity, low voltage {GR}| market for | Cut-off, U
	Output	Dewatered concentrate	0.605	t	Going to rotary drying
		Water	1.32	m^3	Output to nature (Water, unspecified natural origin, GR)
Rotary drying	**Input**	Heat energy[c]	216	MJ	Heat, district or industrial, other than natural gas {Europe without Switzerland}| heat production, heavy fuel oil, at industrial furnace 1 MW | Cut-off, U
		Transportation	0.82	tkm	Transport, freight, lorry 16–32 metric ton, EURO3 {RER}| transport, freight, lorry 16–32 metric ton, EURO3 | Cut-off, U
		Water	27.5	kg	Input from air (moisture acquired during stocking)
	Output	Dried final concentrate	0.578	t	Going to briquetting
		Water	55	kg	Output to air due to evaporation (Water)
Briquetting	**Input**	Electric Energy[d]	31.2	MJ	Electricity, low voltage {GR}| market for | Cut-off, U
	Output	Briquettes	0.578	t	Going to calcination (inventory in Table 4 and 5)

[a] All truck transportation is modelled as trucks of payload 16–32 Euro 3 category. GM reported that the payload of the trucks is 20 tonnes and most of the trucks are of the category Euro 3

[b] Water recirculation within the system was accounted for in the model so that eventually the net water consumption of the system is shown in the water consumption indicator in LCIA

[c] FF developers expected moisture content after dewatering to be around 10%. GM expects that the dewatered concentrate will be stored for long exposed to air so it is expected to catch more moisture from the atmosphere approximated at 5% extra. The dryer is required to drop the 15% to 5%. The heat energy hence the fuel requirements were calculated starting from the specific heat capacity of both, water and magnesite, and the amount of moisture to be removed. The fuel for the rotary drier was assumed to be heavy fuel oil

[d] Information regarding the energy consumption of briquetting was obtained from commercial suppliers of briquetting machines used in mining industry

Table 4 Calcination department inventory of S1.1 referred to the functional unit: inputs

Input flow	Amount	Unit	Ecoinvent dataset/Note
Transportation	0.0685	tkm	Transport, freight, lorry 16–32 metric ton, EURO3 {RER}| transport, freight, lorry 16–32 metric ton, EURO3 | Cut-off, U
Loader	0.0289	tkm	Transport, tractor and trailer, agricultural {RoW}| processing | Cut-off, U
Petcoke	52.1	kg	Petroleum coke {GLO}| market for | Cut-off, U
Heavy Fuel Oil (HFO)	7.03	kg	Heavy fuel oil {Europe without Switzerland}| market for | Cut-off, U
Woodchips	1.52	kg	Wood chips, wet, measured as dry mass {Europe without Switzerland}| market for | Cut-off, U
Sawdust	1.52	kg	Sawdust, wet, measured as dry mass {Europe without Switzerland}| market for sawdust, wet, measured as dry mass | Cut-off, U
Hydrated Lime	11.5	kg	Lime, hydrated, packed {RER}| market for lime, hydrated, packed | Cut-off, U
Electric Energy[a]	59.6	MJ	Electricity, low voltage {GR}| market for | Cut-off, U

[a] The electric energy consumption reported is for the whole calcination department including the flue-gas treatment units

blend will be sunflower seed hulls and olive kernel. GM anticipates that the new blend will reduce the NO_2 emissions by 20%, and SO_2 generated in kilns by 50%. The expected reduction in SO_2 emission will certainly lower the pressure on the desulfurization unit hence hydrated lime ($Ca(OH)_2$) consumption. This was accounted for in the model considering the stoichiometric

Table 5 Calcination department inventory of S1.1 referred to the functional unit: outputs

Output flow	Amount	Unit	Ecoinvent dataset/Note
Magnesia	0.239	t	Final product
Avoided primary magnesia	0.194	t	Magnesium oxide {RER}| production | Cut-off, U[a]
Unrecycled dust to landfilling	26.8	kg	Inert waste, for final disposal {CH}| treatment of inert waste, inert material landfill | Cut-off, U
Direct emissions to air			
CO_2, fossil	378	kg	Emissions to air, low pop
CO_2, biogenic[b]	5.3	kg	Emissions to air, low pop
CO, fossil[b]	1.04	kg	Emissions to air, low pop
SO_2	1.51	kg	Emissions to air, low pop
NO_2	1.05	kg	Emissions to air, low pop
Particulates[c], > 2.5 um, and < 10um	0.03	kg	Emissions to air, low pop
Antimony[d]	2.93E-5	kg	Emissions to air, low pop
Arsenic[d]	2.93E-5	kg	Emissions to air, low pop
Lead[d]	2.93E-5	kg	Emissions to air, low pop
Chromium[d]	2.93E-5	kg	Emissions to air, low pop
Cobalt[d]	2.93E-5	kg	Emissions to air, low pop
Copper[d]	2.93E-5	kg	Emissions to air, low pop
Manganese[d]	2.93E-5	kg	Emissions to air, low pop
Nickel[d]	2.93E-5	kg	Emissions to air, low pop
Vanadium[d]	2.93E-5	kg	Emissions to air, low pop

[a] Heat energy amount and source (i.e. fuel) in ecoinvent dataset was not coherent with neither the data provided by GM nor the average production of Magnesia in Europe reported in Best Available Techniques (BAT) (Schorcht et al. 2013). To move on with the analysis, the dataset was manually modified according to the BAT to represent the average technology in Europe. In the model, heat energy was taken as 9 GJ/ tonne MgO produced (range in BAT 6–12 GJ) distributed equally between the three dominating fuels in Europe in magnesia production (i.e. petcoke, heavy fuel oil, and natural gas)

[b] The distinction between fossil CO_2 (generated from the magnesite decomposition and fossil fuel burning), and biogenic CO_2 (generated from biomass) was made by deducting the biogenic CO_2 from the GM reported CO_2 emissions. The associated biogenic CO_2 was calculated starting from the carbon content of the wood (≈47.5%wt) and stoichiometric ratio (Chandrasekaran et al. 2012).

[c] Most of the particulate matter or dust is captured in ESP and bag filters, however a low fraction escapes anyway and emitted to air. The extracted dust from these units is then partially recycled, and the rest is discarded in stockpiles which was modelled as inert landfilling

[d] Heavy metals were reported by GM all together as < 0.5 mg/Nm^3 of flue gas. An approximation was made in SimaPro taking half of the 0.5 mg (similar practice was done in other work, see for example Caserini et al. 2004) and dividing it over 9 (i.e. number of metals reported)

Table 6 Inventory of S2.0 referred to the functional unit: inputs

Input flow	Amount	Unit	Ecoinvent dataset/Note
Transportation	0.719	tkm	Transport, freight, lorry 16–32 metric ton, EURO3 {RER}| transport, freight, lorry 16–32 metric ton, EURO3 | Cut-off, U
Loader	0.05	tkm	Transport, tractor and trailer, agricultural {RoW}| processing | Cut-off, U
Petcoke	90.2	kg	Petroleum coke {GLO}| market for | Cut-off, U
HFO	12.2	kg	Heavy fuel oil {Europe without Switzerland}| market for | Cut-off, U
Woodchips	2.64	kg	Wood chips, wet, measured as dry mass {Europe without Switzerland}| market for | Cut-off, U
Sawdust	2.64	kg	Sawdust, wet, measured as dry mass {Europe without Switzerland}| market for sawdust, wet, measured as dry mass | Cut-off, U
Hydrated Lime	20	kg	Lime, hydrated, packed {RER}| market for lime, hydrated, packed | Cut-off, U
Electric Energy[a]	103	MJ	Electricity, low voltage {GR}| market for | Cut-off, U

[a] Please refer to footnotes in Table 4

ratio of the desulfurization equation. The potential reduction in fossil CO_2 emissions was calculated starting from the carbon content of the new biomass and petcoke. GM reported the carbon content of the tested biomass as 50.58%d.b. with biomass moisture content of 5.5%w.b. The carbon content of the petcoke in the calculations was taken as 81.12%wt assuming sponge petcoke (Miller 2015). The inventory of the improved calcination is reported in Sect. 4 in supplementary materials.

S1.3 and S2.3 represent even better future scenarios with new low-NOx burners that are expected to cut the NOx emitted by 25% according to GM.

3 Impact assessment results and discussion

The life cycle impact assessment (LCIA) results are calculated with Environmental Footprint LCIA method *(EF 3.0)* which includes 16 impact categories: Climate Change (CC), Ozone Depletion (OD), Ionizing radiation (IR), Photochemical ozone formation (PCOF), Particulate matter (PM), Human toxicity, non-cancer (HT, non-cancer), Human toxicity, cancer (HT, cancer), Acidification (AD), Eutrophication, freshwater (EU, freshwater), Eutrophication, marine (EU, marine), Eutrophication,

Table 7 Inventory of S2.0 referred to the functional unit: outputs

Output flow	Amount	Unit	Ecoinvent dataset/Note
Magnesia	0.414	t	Final product
Avoided primary magnesia	0.332	t	Magnesium oxide {RER}| production | Cut-off, U[a]
Unrecycled dust to landfilling	46.3	kg	Inert waste, for final disposal {CH}| treatment of inert waste, inert material landfill | Cut-off, U
Direct emissions to air			
CO_2, fossil[b]	653	kg	Emissions to air, low pop
CO_2, biogenic[b]	9.19	kg	Emissions to air, low pop
CO, fossil	1.79	kg	Emissions to air, low pop
SO_2	2.6	kg	Emissions to air, low pop
NO_2	1.82	kg	Emissions to air, low pop
Particulates[c], > 2.5 um, and < 10um	0.0534	kg	Emissions to air, low pop
Antimony[d]	5.08E-5	kg	Emissions to air, low pop
Arsenic[d]	5.08E-5	kg	Emissions to air, low pop
Lead[d]	5.08E-5	kg	Emissions to air, low pop
Chromium[d]	5.08E-5	kg	Emissions to air, low pop
Cobalt[d]	5.08E-5	kg	Emissions to air, low pop
Copper[d]	5.08E-5	kg	Emissions to air, low pop
Manganese[d]	5.08E-5	kg	Emissions to air, low pop
Nickel[d]	5.08E-5	kg	Emissions to air, low pop
Vanadium[d]	5.08E-5	kg	Emissions to air, low pop

[a,b,c,d] Please refer to footnotes in Table 5

Table 8 Inventory of S2.1 referred to the functional unit

Unit process		Flow	Amount	Unit	Ecoinvent dataset/Note
Wet milling and pumping	**Input**	Transportation[*a]	0.171	tkm	Transport, freight, lorry 16–32 metric ton, EURO3 {RER}| transport, freight, lorry 16–32 metric ton, EURO3 | Cut-off, U (From beneficiation to wet milling)
		Electric energy	3.7	MJ	Electricity, low voltage {GR}| market for | Cut-off, U
		Water[b]	0.228	m^3	Input from nature (Water, unspecified natural origin, GR)
	Output	Milled < 4 mm fines	0.571	t	Going to FF flotation plant
FF flotation plant (incl. cleaner and scavenger)	**Input**	Collector (Resanol)	171	g	See Sect. 2 in supplementary materials
		Depressant (Sodium Hexametaphosphate)	68.6	g	Sodium tripolyphosphate {GLO}| market for | Cut-off, U (See Sect. 2 in supplementary materials)
		Water	0.571	m^3	Input from nature (Water, unspecified natural origin, GR)
		Electric energy	1.23	MJ	Electricity, low voltage {GR}| market for | Cut-off, U
	Output	Final concentrate	0.851	t	Going to dewatering of final concentrate
		Tailing to dewatering	0.291	t	Going to dewatering of tailing (Sect. 3 in supplementary materials)
Dewatering of final concentrate (Thickener (Derrick screens)/ filtration)	**Input**	Electric energy	0.439	MJ	Electricity, low voltage {GR}| market for | Cut-off, U
	Output	Dewatered concentrate	0.268	t	Going to rotary drying
		Water	0.584	m^3	Output to nature (Water, unspecified natural origin, GR)
Rotary drying	**Input**	Heat energy[c]	96.1	MJ	Heat, district or industrial, other than natural gas {Europe without Switzerland}| heat production, heavy fuel oil, at industrial furnace 1 MW | Cut-off, U
		Transportation	0.365	tkm	Transport, freight, lorry 16–32 metric ton, EURO3 {RER}| transport, freight, lorry 16–32 metric ton, EURO3 | Cut-off, U
		Water	12.2	kg	Input from air (moisture acquired during stocking)
	Output	Dried final concentrate	0.256	t	Going to briquetting
		Water	24.4	kg	Output to air due to evaporation (Water)
Briquetting	**Input**	Electric Energy[d]	13.8	MJ	Electricity, low voltage {GR}| market for | Cut-off, U
	Output	Briquettes	0.256	t	Going to calcination (inventory in Table 9 and 10)

[*] The transportation input to wet milling represents the distance between beneficiation department and future wet milling unit. It was assumed to be 500 m which is the same distance between stockpile of fines and wet milling in S1.1

[a,b,c,d] Please refer to footnotes of Table 3

Table 9 Calcination department inventory of S2.1 referred to the functional unit: inputs

Input flow	Amount	Unit	Ecoinvent dataset/Note
Transportation	0.498	tkm	Transport, freight, lorry 16–32 metric ton, EURO3 {RER}| transport, freight, lorry 16–32 metric ton, EURO3 | Cut-off, U
Loader	0.049	tkm	Transport, tractor and trailer, agricultural {RoW}| processing | Cut-off, U
Petcoke	82.5	kg	Petroleum coke {GLO}| market for | Cut-off, U
HFO	11.1	kg	Heavy fuel oil {Europe without Switzerland}| market for | Cut-off, U
Woodchips	2.41	kg	Wood chips, wet, measured as dry mass {Europe without Switzerland}| market for | Cut-off, U
Sawdust	2.41	kg	Sawdust, wet, measured as dry mass {Europe without Switzerland}| market for sawdust, wet, measured as dry mass | Cut-off, U
Hydrated lime	18.3	kg	Lime, hydrated, packed {RER}| market for lime, hydrated, packed | Cut-off, U
Electric energy[a]	94.3	MJ	Electricity, low voltage {GR}| market for | Cut-off, U

[a] please refer to footnotes of Table 4

terrestrial (EU, terrestrial), Ecotoxicity, freshwater (ET, freshwater), Land use (LU), Water use (WU), Resources use, fossil (RU, F), and Resource use, minerals and metals (RU, M).

3.1 Case 1

Table 11 compares the impact indicators results of S1.0 and S1.1. The current way of handling the discarded fines showed better environmental performance in 11 impact categories, whereas all the results with negative values indicate a preference of fines treatment with FF technology. These impact categories are ionizing radiation, particulate matter, human toxicity-cancer, human toxicity-non cancer, and freshwater ecotoxicity. The ratio between future and present results are generally very significant as it can be seen from the column “S1.1/S1.0”.

These results can initially seem unforeseen given that a landfilling process is being compared with a material recovery process. However, to understand the reasons behind these results, further analysis of the future system was necessary given its complexity. Figure 6 shows the contribution analysis of the future system to help detect the hotspots and how they can be mitigated. The

Table 10 Calcination department inventory of S2.1 referred to the functional unit: outputs

Output flow	Amount	Unit	Ecoinvent dataset/Note
Magnesia	0.378	t	Final Product
Avoided primary magnesia	0.323	t	Magnesium oxide {RER}| production | Cut-off, U[a]
Unrecycled dust to landfilling	42.4	kg	Inert waste, for final disposal {CH}| treatment of inert waste, inert material landfill | Cut-off, U
Direct emissions to air			
CO_2, fossil[b]	597	kg	Emissions to air, low pop
CO_2, biogenic[b]	8.4	kg	Emissions to air, low pop
CO, fossil	1.64	kg	Emissions to air, low pop
SO_2	2.38	kg	Emissions to air, low pop
NO_2	1.668	kg	Emissions to air, low pop
Particulates[c], >2.5 um, and <10um	0.049	kg	Emissions to air, low pop
Antimony[d]	4.65E-5	kg	Emissions to air, low pop
Arsenic[d]	4.65E-5	kg	Emissions to air, low pop
Lead[d]	4.65E-5	kg	Emissions to air, low pop
Chromium[d]	4.65E-5	kg	Emissions to air, low pop
Cobalt[d]	4.65E-5	kg	Emissions to air, low pop
Copper[d]	4.65E-5	kg	Emissions to air, low pop
Manganese[d]	4.65E-5	kg	Emissions to air, low pop
Nickel[d]	4.65E-5	kg	Emissions to air, low pop
Vanadium[d]	4.65E-5	kg	Emissions to air, low pop

[a,b,c,d] please refer to footnotes of Table 5

Table 11 LCIA results of S1.0 and S1.1 (referred to functional unit)

Impact category	Unit	S1.0	S1.1	S1.1/S1.0
CC	kg CO$_2$ eq	4.31E+00	9.31E+01	21.58
OD	kg CFC11 eq	2.12E-06	1.56E-05	7.39
IR	kBq U-235 eq	6.66E-01	-6.33E-01	-0.95
PCOF	kg NMVOC eq	4.99E-02	8.86E-01	17.75
PM	disease inc	9.30E-07	-5.05E-05	-54.34
HT, non-cancer	CTUh	3.70E-08	-1.15E-05	-310.74
HT, cancer	CTUh	1.78E-09	-7.05E-07	-396.45
AD	mol H+eq	4.21E-02	1.99E+00	47.25
EU, freshwater	kg P eq	2.46E-04	4.12E-02	167.52
EU, marine	kg N eq	1.59E-02	3.21E-01	20.16
EU, terrestrial	mol N eq	1.75E-01	3.34E+00	19.15
ET, freshwater	CTUe	7.69E+01	-8.30E+03	-107.99
LU	Pt	3.06E+02	3.94E+02	1.29
WU	m3 depriv	4.37E-01	1.54E+01	35.30
RU, F	MJ	1.38E+02	6.06E+02	4.38
RU, M	kg Sb eq	8.51E-06	1.69E-04	19.88

contributors are the main unit processes starting with wet milling and ending up with magnesia production in calcination. Except for a few impact indicators (water use and resources use of minerals and metals where FF flotation has some significant contribution), the prevalence of calcination above all other processes can be seen. The impacts from calcination are linked to either the petcoke supply chain or the direct emissions to air from the combustion process in the kilns. Theoretically, the decomposition of magnesite in the kilns can only contribute to CO$_2$ emissions while all the other emissions like NOx, SOx are generated from the fuels. That leads to believe that the low performance of the future scenario is due to the newly added burden of calcinating the fines after flotation which obviously does not exist in the current scenario. It can also be concluded that the type of combustion fuel plays an important role here.

The FF flotation unit impact on water use is evident given that water is essential in this process and same applies to wet milling which also contributes to this impact category. Most of this water is recovered later in the dewatering of concentrate and tailings, nevertheless

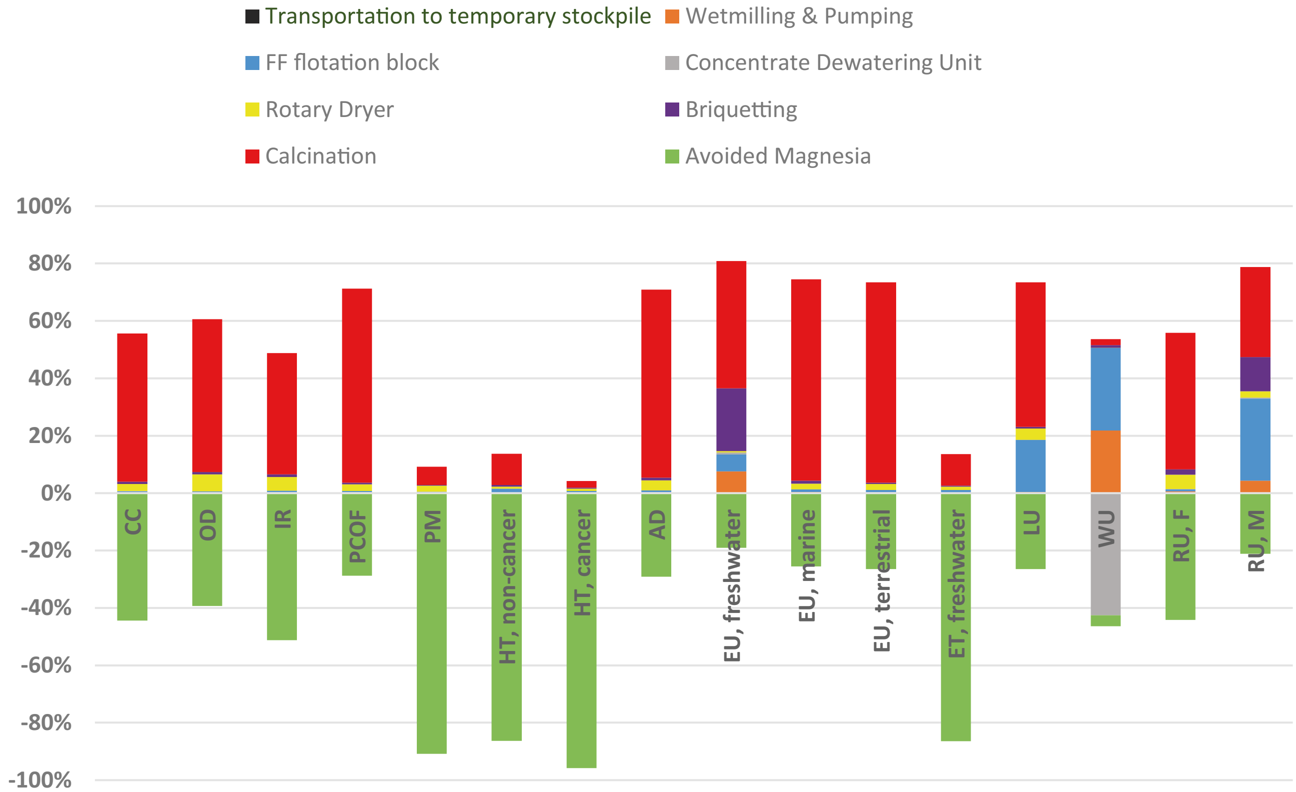
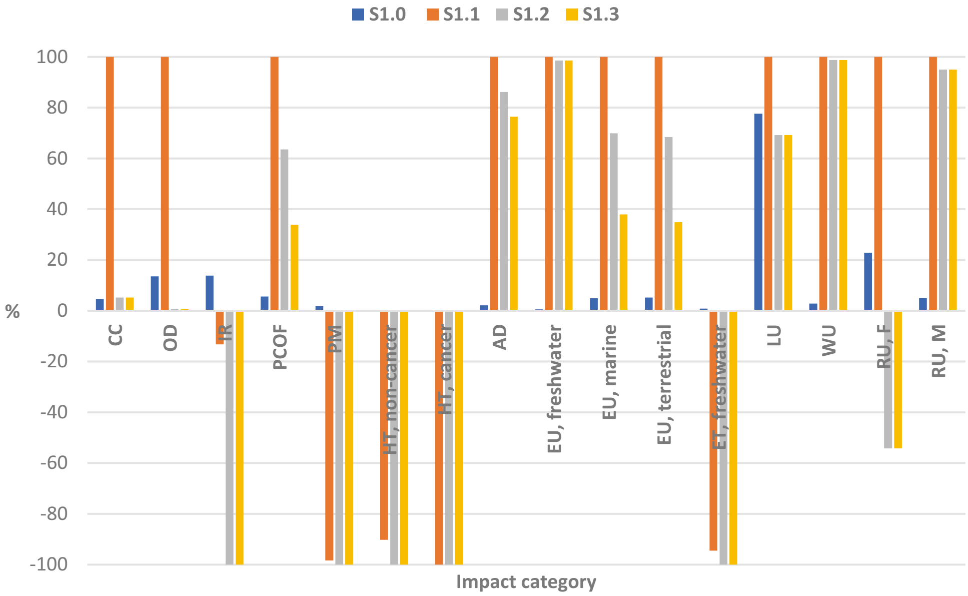


Fig. 6 Contribution analysis of S1.1

Fig. 7 Comparing impact assessment results of S1 scenarios



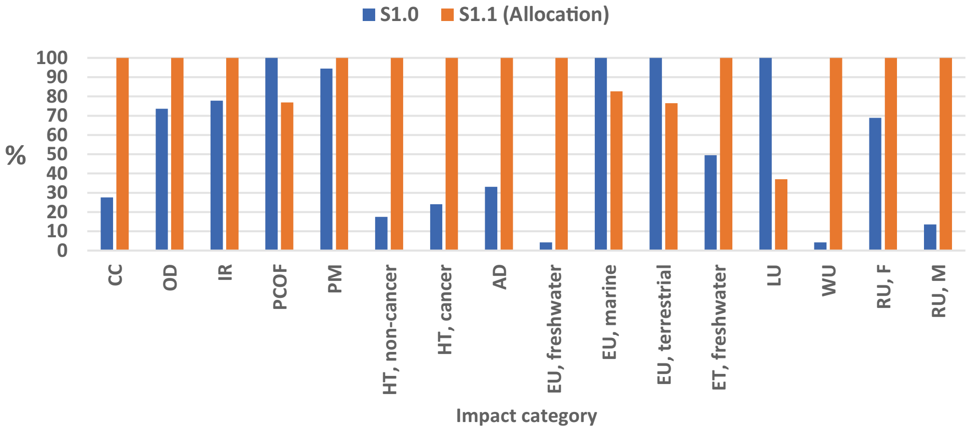
the net water consumption slight shifts into the positive domain (Fig. 6) which indicates that it is not exactly a closed loop because clearly the dewatering units are not 100% efficient.

The second contribution of FF is in mineral resources consumption, and it is due to the consumption of the sodium salts which are constituents of collector and depressant. Nevertheless, it was found odd that the avoided technology does not contribute to this impact category knowing that by avoiding primary production of magnesia, raw magnesite extraction from nature is avoided as result. The reason behind that was the absence of a characterization factor of raw magnesite in EF3.0 LCIA method. Consequently, the benefit of avoided consumption of raw magnesite ore are not seen under this impact category even if the inventory results showed that the upgrade of 1 tonne of fines by FF can save at least 440 kg of raw magnesite ore in ground. Unfortunately, none of the explored LCIA methods categorizes magnesite under mineral resources depletion impact category, however it is critical to highlight this aspect given that the ultimate objective of FF project is the conservation of raw materials. Obviously, this benefit does not exist in the present case (S1.0).

3.1.1 Results of the improved scenarios S1.2 and S1.3

The improved calcination in S1.2 and S1.3 resulted in remarkable benefits in nine impact categories (Fig. 7). For example, climate change indicator result becomes almost equal to the stockpiling scenario showing a tremendous drop of around 95% of previous value obtained in S1.1. The other seven impact categories (PM, HT (non-cancer & cancer), EU (freshwater), water use, ET (freshwater) and RU (M)) were barely affected because calcination has limited influence on them. Compared to the current stockpiling scenario

Fig. 8 Comparison of the LCIA results of S1.0 and S1.1 when allocation is applied



(S1.0), the improved calcination makes the FF future scenarios noticeably preferred in 8 out of 16 impact categories compared to only 5 in S1.1. The three new impact categories are OD, LU, and RU (F) thanks to the substantial cut in petcoke consumption which results in less Halons emissions, reduced mining land and fossil resources depletion.

S1.3 is even step ahead from S1.2. Impact categories like EU (marine), EU (terrestrial), and PCOF showed more than 20% drop from S1.2 to S1.3 thanks to the new low NOx burners. This is expected given that these impact categories were initially driven by the NO_2 emissions to air.

3.1.2 Allocation as an alternative to solve multifunctionality

As mentioned before, physical allocation was applied to verify the robustness of conclusions in system expansion given the uncertainties associated with the substituted technology. Figure 8 illustrates the relative results of S1.1 when allocation is applied compared to S1.0.

In this case, S1.1 shows better performance in only four impact categories which are PCOF, EU (marine), EU (terrestrial), and LU. Interestingly, these impact categories are different than what was obtained when system expansion was adopted. This is mainly due to the exclusion of calcination impact. With allocation, it appears that the main problem related to future scenarios is the fuel combustion in the rotary drier followed by electricity in most of impact categories.

These results demonstrate how multifunctionality solving approach can heavily affects the results obtained. Nonetheless, the general conclusion with allocation remains in line with what was obtained with system expansion: the future scenario scores lower impacts in a minority of impact categories when compared to current discarding of fines. The results are expected to be identical if calculated for S1.2 or S1.3 instead of S1.1 given that nothing of calcination inventory will be allocated to the functional unit anyway.

3.2 Case 2

Figure 9 illustrates the comparison between the calcination of current kiln feed vs the calcination of future higher quality kiln feed thanks to FF technology (i.e. S2.0 and S2.1). The comparison shows very little differences (around 10%) between the two scenarios in most impact categories. The exception to this pattern is in five impact categories (CC, EU (freshwater), WU, RU (F), and RU (M)): S2.1 exhibits considerably less impact in CC and RU (F) while S2.0 showed

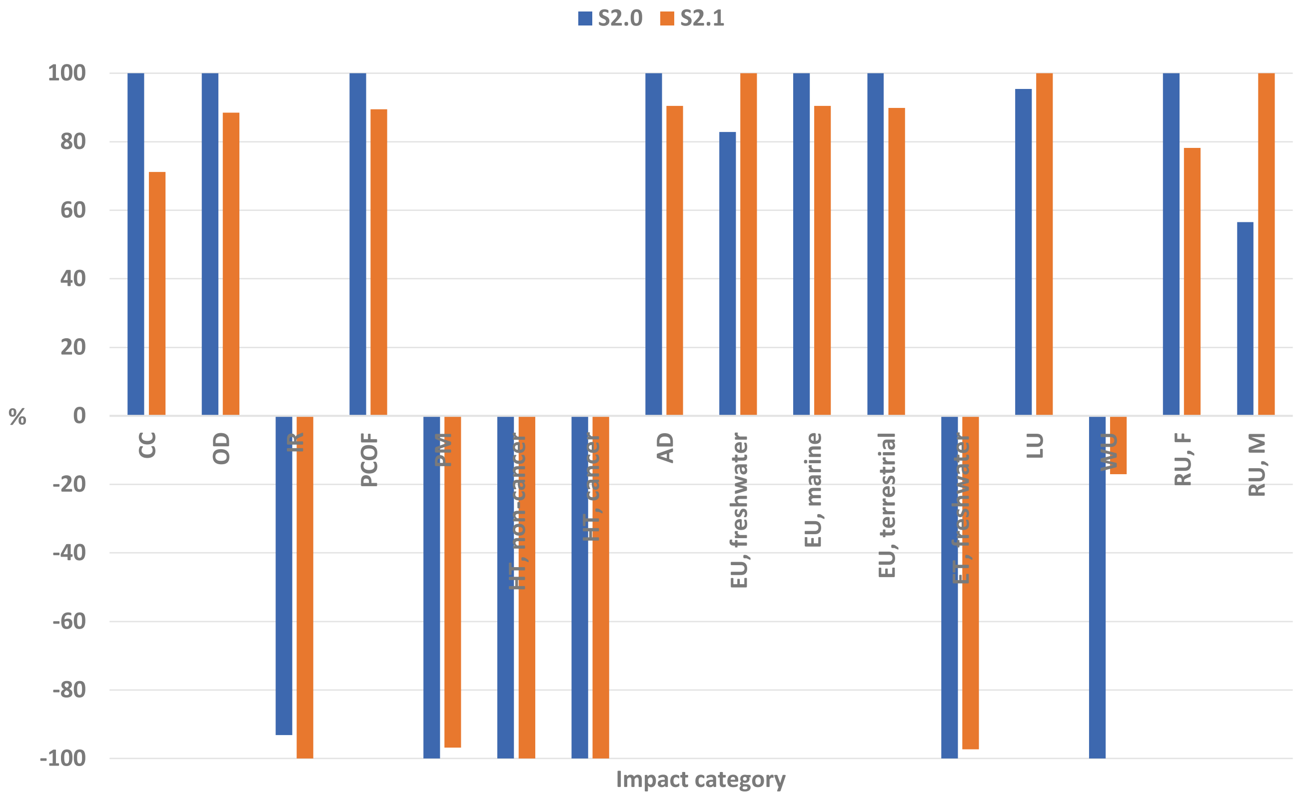


Fig. 9 LCIA results comparison between S2.0 and S2.1

better results in the other three impact categories. Calcination is the main contributor to impacts in the two scenarios despite that the contribution varies quantitively between the two scenarios.

The key factor in calcination impact is the ratio between required calcination in GM system and the avoided primary production and how this ratio affects each impact category differently. The avoided primary magnesia production/ F.U. is more in S2.0. On the contrary, S2.1 is associated with less calcination required in the foreground system due to the losses in FF tailings so at the end the amount to be calcinated per F.U. is less than that in S2.0 but its product has better quality. This is all from life cycle inventory point of view, but this fact affects each impact category differently when the inventory is transformed into impacts. For example, the added impact of calcination in climate change is 656 kg CO_2 eq. and 600 kg CO_2 eq./ F.U. for S2.0 and S2.1 respectively whereas the avoided impact is 304 kg CO_2 eq. and 296 kg CO_2 eq/ F.U. for S2.0 and S2.1 respectively. The difference in added impact here is more than the difference in the avoided impact, therefore S2.1 is favoured over S2.0 thanks to the lower net impact. The same concept applies in RU (F) impact category in which the fuel consumption in calcination is the problem and to a much lesser extent electricity which has a more evident impact in RU (minerals and metals), freshwater eutrophication, and water use impact categories.

Despite that electricity plays a minor role in the overall impacts, some other impact categories are very sensitive to electricity consumption. Although the biggest part of the entire electricity consumption takes place in calcination, the S2.1 is clearly associated with higher electricity consumption due to the extra machinery needed, so it can be seen as a drawback in these impact categories. This is the case in RU (minerals and metals), EU (freshwater), and WU.

3.2.1 Results of the improved scenarios S2.2 and S2.3

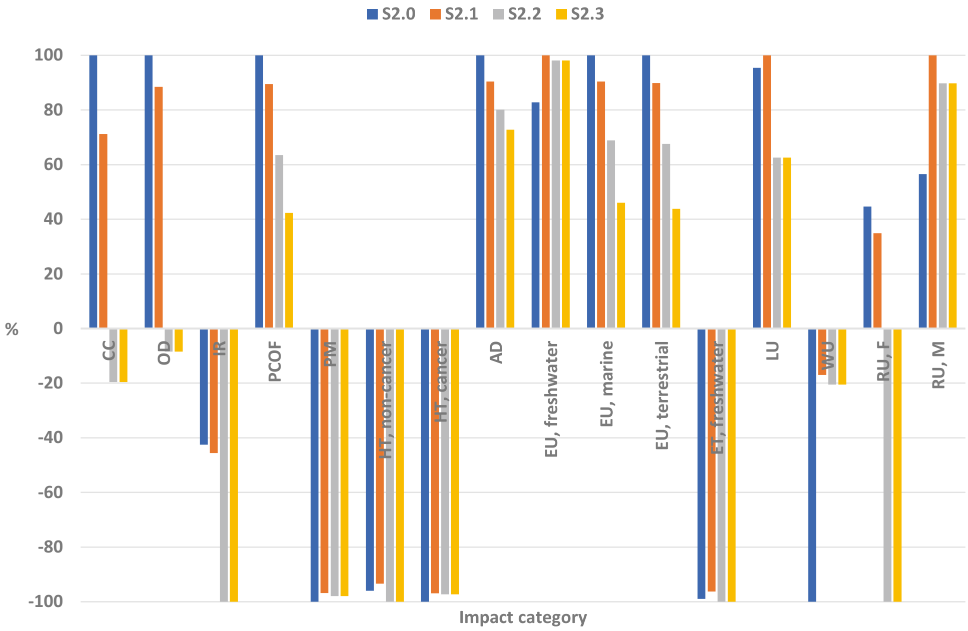
The S2.2 and S2.3 of improved calcination showed significant environmental benefits compared to S2.0 and S2.1 scenarios. Figure 10 shows an overview on the performance of each scenario.

PM, HT (non-cancer), HT (cancer), and ET are showing almost equal results in all scenarios which means that improvements in calcination are not influencing these impact categories. Moreover, no significant benefits were gained in EU (freshwater), WU, nor in RU (M) in which S2.0 without FF technology is still better.

Nonetheless, the rest of impact categories are substantially positively affected by the improvements. CC and OD for example has switched to the negative domain thanks to the petcoke reduction which is associated with significant reduction in fossil CO_2 emissions in kilns, and Halons emission from its supply chain. The same trend is noticed in IR, PCOF, AD, EU (marine), EU (terrestrial), LU, and RU (F), mostly the impact categories that are sensitive to fuel supply and combustion emissions.

The four scenarios were additionally compared after normalization and weighting using default EF3.0 values to give the final score in environmental points. The weighting results are -12.5, -13.2, -19, -20.1 mPt/ F.U. for S2.0, S2.1, S2.2 and S2.3 respectively. With these results, it can be clearly said that combining FF flotation with the improved calcination is an ideal formula from an environmental point

Fig. 10 Comparing impact assessment results of S2 scenarios



of view. Moreover, the significant drop between -13.2 to -19 indicates the need to prioritize improving the fuel mix.

3.2.2 Electric energy sensitivity analysis

One of the highly uncertain data is the electric energy consumption of the new machineries including the flotation unit itself. Furthermore, results showed that electric energy consumption plays an important role in some impact categories. Therefore, the following sensitivity analysis was carried out assuming a hypothetical increase of 25% and 50% in the electric energy consumption in the new machines (i.e. milling, FF flotation, dewatering, briquetting) which have baseline consumption of around 5.3 kWh/F.U. Running this sensitivity analysis was also suggested by GM experts as they considered the electric figure provided for the new units to be a very rough approximation and can lead to underestimation of the consumed energy. The analysis is applied to the worst and the best future scenarios (i.e. S2.1 and S2.3) at the weighting step of LCIA phase and the results are reported in Sect. 5 in supplementary materials. The results demonstrated that even with 50% more electric energy consumption, the environmental score remains almost the same within the same future scenario.

4 Conclusions and recommendations

In this study two prospective comparative LCAs were conducted showing two different applications of an emerging froth flotation technology developed for the mining industry. The two LCAs were done in the context of Grecian Magnesite beneficiation plant in Greece where magnesite ore is mined, beneficiated and calcinated to produce magnesia. The first LCA study compares the current disposal of wet residues from beneficiation line in a form of fine particles with granular size < 4 mm against minerals recovery from these fines using FF technology. The second LCA concerns upgrading beneficiated magnesite concentrate with the new technology before firing it in calcination kilns aiming at higher quality magnesia eventually.

The LCA results did not totally support the application of the new technology whether for the first case or the second one. Nonetheless, the second option seemed like a preferred option according to the results. Results also showed that the quality of the recovered concentrate has crucial impact on the results, however this conclusion is highly dependent on the modelling choices made especially when substitution by system expansion was applied. Furthermore, the result showed that calcination is the hot spot in both cases with the supply and firing the petcoke being the key factor. Consequently, a greener fuel mix with higher biomass shares led to a huge improvement in the overall performance of calcination when tested, thus it is recommended that FF technology be accompanied with GM strategies on cleaner fuels and better kilns regardless its future application. In addition to traditional system expansion approach to tackle multifunctionality, a new allocation method is proposed. While allocation results were not identical to system expansion, it led to similar final conclusions.

It was also concluded that electric energy consumption of the new units of FF technology is not very impactful whether in case 1 or 2. A sensitivity analysis proved the insignificance even with 50% increase in the expected consumption. Similarly, the water consumption can be tolerated if proper water recirculation systems are established.

Despite the modest overall performance, a particular benefit of recovering the < 4 mm fines with FF technology is from raw materials preservation point of view. Inventory results showed around 440 kg of avoided virgin material extraction per 1 tonne of fines recovered. This value is based on calculations from ecoinvent database, however field experience from GM expects even higher values than the calculated 440 kg.

It is important to underline that these results and conclusions are specific to GM case study. This means that another beneficiation system with the same new technology will give different results particularly with another type of metal or mineral beneficiation system. Furthermore, as any in LCA, there are limitations to the study. Even though most of these limitations are characteristic of prospective LCAs like upscaling uncertainty, some are specific to the study such as the inventory irregularities in ecoinvent substituted technology of magnesium oxide production. Despite tackling the issue by applying the essential corrections, it adds to the uncertainty. Moreover, the choice of the way to calculate the substitution ratio is also quite subjective.

Future studies can work on improving the modelling of tailings pond in tailing treatment facility which can be refined to include more of operation impacts or including emissions to soil from ponds if such data will be available in the future. Similarly, the modelling of flotation reagents (i.e. collector and depressant) can be improved with better data. Last but not least, the upscaling of unit processes to full commercial scale can also be improved given that linear upscaling from lab tests was a dominant technique in this study due to scarcity of better data. One suggestion can be comparing data from lab tests and pilot tests whenever these tests are concluded hence trying to derive more representative relations between operational parameters when the system is upscaled from lab scale to pilot scale. The derived relations can then be used to predict how these operational parameters will become in a full industrial deployment hence more accurate LCA inventory can be calculated.

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Data availability All data generated or analysed during this study refer to Grecian Magnesite Company (https://www.grecianmagnesite.com/) and FineFuture Project (https://finefuture-h2020.eu/).

Declarations

Conflict of interests 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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