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The environmental performance of mining operations: Comparison of alternative mining solutions in a life cycle perspective

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A R T I C L E I N F O

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A B S T R A C T

Mining represents the first step to the access to mineral resources. The impacts induced by such operations now contribute to the impacts of a wide range of goods and services, given the widespread use of these raw materials in the worldwide economy. In this context, this study aims at assessing the environmental performance of mining operations in a life cycle perspective, considering two currently operating mine sites: the Erzberg iron open-pit mine (Austria) and the Lujar fluorspar underground mine (Spain). In particular, this study aims at i) identifying the main environmental hotspots along the cradle-to-gate exploitation of mineral deposits in these two mines ("reference scenarios"), ii) assessing the environmental performance of two alternative mining solutions ("alternative scenarios"), respectively the use of alternative explosive compositions (including their associated air emissions) and the implementation of a new blast design method. This assessment relies on representative sets of data primarily drawn from on-site operations and experimental results, completed with other data sources to fill the gaps. The environmental impacts are characterized based on the European EF (Environmental Footprint) life cycle impact assessment method. Firstly, among the 16 impact categories considered, the production of 1 ton of iron concentrate (33.5% Fe) in the Erzberg mine in particular potentially induces a total of 8.75 kg CO_2-eq. The consumption of ferrosilicon in the concentration step (main contributor to 8 impact categories out of 16), of steel in the comminution step (main contributor to 2 impact categories), and of diesel by the machinery necessary for loading/hauling the ore (main contributor to 3 impact categories) stand for the main environmental hotspots in the Erzberg case. Secondly, the production of 1 ton of fluorspar concentrate (79.2% CaF_2) in the Lujar mine potentially induces a total of 174 kg CO_2-eq. The consumption of diesel by the machinery and the on-site generators in the mining and loading/hauling steps (main contributor to 11 impact categories out of 16), along with the mine infrastructure/equipment (main contributor to 4 impact categories) are identified as the main environmental hotspots in the Lujar case. The implementation of both alternative mining solutions results in relatively limited environmental effects on the overall life cycle environmental performance of the Erzberg mining operations (less than 3% difference in terms of impacts). Finally, this study highlights that some challenges still remain to be addressed in order to better secure the use of life cycle assessment in the mining context, in particular in terms of data monitoring/measurement or impact assessment methods.

1. Introduction

In 2008, the Raw Materials Initiative set out a strategy for a more reliable and secure access to raw materials in Europe, crucial to the competitiveness and growth of the European Union (EU) economy (European Commission, 2008). The access to resources is considered a strategic security question by the European Commission (EC), which

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Abbreviations and nomenclature

ANFO	Ammonium Nitrate Fuel Oil
CaF_2	Fluorspar
CO	Carbon monoxide
CO_2	Carbon dioxide
E682	Reference of a pure emulsion-based explosive
Fe	Iron
FeSi	Ferrosilicon
GWP	Global Warming Potential
LCA	Life Cycle Assessment
NH_3	Ammonia
NOx	Nitrogen oxides
SOx	Sulfur oxides

requires ensuring the supply of sustainable raw materials (European Commission, 2019). In particular, mineral resources and metals are now key components of many final or intermediate products used in society. Mining and mineral processing are the cradle of their production, the impacts of these activities accordingly contribute to the impacts of many products. More generally, raw materials both hinder and contribute to the 17 Sustainable Development Goals established by the UN 2030 Agenda (Mancini et al., 2019).

The environmental impacts of mining and mineral processing may be considered with different views. One of these views is the "mining project" view, under which the impacts are generally considered in light of risk mitigation actions according to territorial legislations in force. Basically, a mining project is submitted to a regulatory-driven impact assessment (IA) covering many aspects of potential pollution releases across the entire process chain, i.e. from the ore extraction to its concentration. Among the main impacts to manage on a mine site, those related to mining (in particular blasting) operations include: ground vibrations (Folchi, 2003; Kuzu and Ergin, 2005; Bhandari, 2016; Jahed Armaghani et al., 2015), air blast overpressure (Kuzu and Ergin, 2005; Bhandari, 2016; Jahed Armaghani et al., 2015), dust (Folchi, 2003; Bhandari, 2016), fly rocks (Folchi, 2003; Bhandari, 2016; Jahed Armaghani et al., 2015), noise (Folchi, 2003; Monjezi et al., 2009; Saviour, 2012), nitrates leaching into water or soil (Forsyth et al., 1995).

On another note, for more than 20 years, life cycle assessment (LCA) has continuously gained interest for comparing potential environmental impacts of products and services, to the point that its use has become widespread as a support to both policy and company decision-making. LCA has been integrated into several EU environmental policies over the last two decades, e.g. to help define emerging problems (especially related to products and their supply chains, and new technologies) and to help identify policy options (Sala et al., 2016; Sonnemann et al., 2018). By definition, LCA enables undertaking a life cycle perspective, accordingly enlarging the scope of the IA by including upstream and downstream impacts associated with metals production. In particular, given sufficient data, it can enable assessing the contributions of each operation of production to the whole cradle-to-gate impacts of a concentrate or metal production. It enables accounting for both the impacts directly generated by the mine and indirectly generated along the supply-chains the mine is interlinked with. LCA accordingly enables identifying any potential burden-shifting (from one impact category to the other, or from one life-cycle phase to the other) in the comparison of different scenarios. However, it may be noted that, while the IA in the mining project view is spatially and temporally explicit, the life cycle approach generally aggregates emissions across space and time. For example, such a distinction may be relevant regarding dust and pollutants emissions, which are aggregated in space and time in LCA, thus resulting in impacts not representative of actual health risks.

The implementation of LCA highlights that mining and concentration stages may have relatively large contributions to the cradle-to-gate environmental impacts of metals production (Nuss and Eckelman, 2014), depending on the metal and the impact categories considered. For example, the production of iron (Fe) ore generates relatively low environmental impacts on a per kilogram basis among the 63 metals considered by Nuss and Eckelman; however, in the meantime, iron is among the most impactful metals due to its significant global production volume. Among the main environmental hotspots of the iron mining industry, Ferreira and Leite (2015) identify the consumption of electricity as well as grinding media in the iron ore treatment stage as two of the main contributors to the global warming potential (GWP) impacts of iron concentrate production in Brazil; while Norgate and Haque (2010) identify the loading/hauling and crushing/blending steps as the main sources of GWP impacts in the case of iron mining in Australia. Despite these examples of LCA application in the mining industry, assessing the environmental impacts of this sector remains relatively challenging, in particular due to a certain lack of interactions between LCA practitioners and the mining industry (Awuah-Offei and Adekpedjou, 2011). This, in turn, may be partly attributed to the hitherto weak business case for mining companies to undertake LCAs or generate data suitable for input into LCA (Alvarenga et al., 2019).

In this context, this study aims at assessing the environmental performance of mining operations in a life cycle perspective, respectively considering the production of an iron concentrate in the Erzberg (Austria) open-pit mine, and the production of a fluorspar (CaF_2) concentrate in the Lujar (Spain) underground mine. The objective is twofold: i) to identify the main environmental hotspots along the cradle-to-gate exploitation of mineral deposits in these two mines and ii) to analyze the environmental performance of alternative mining solutions to identify potential perspectives for improving the environmental performance of the Erzberg mine. This study is based on representative sets of data, primarily drawn both from currently operating plants ("reference cases studies") and experimental tests ("alternative scenarios").

2. Material and method

2.1. Case studies description

2.1.1. Erzberg mine

Erzberg is an open-pit iron ore mine located in Eisenerz (Austria). It is considered as the biggest deposit of siderite ($FeCO_3$) in the world, the iron content within this mineral amounting to about 40%. Other iron minerals found in this deposit are primarily ankerites ($Ca(Fe,Mg,Mn)(CO_3)_2$), with an iron content varying from 10 to 17%. Currently, the mine annually blasts 12 million tons of ore and waste rock to produce 3 million tons of concentrate (also referred to as fine ore) as final product. Depending on the iron content within the material, different ore fractions are considered:

- < 22% Fe: cut-off grade below which the material is considered as waste;
- 22–30% Fe: low quality ore also called "middlings";
- > 30% Fe: high quality ore (in the following referred to as "rich fraction").

The waste rock, with an iron content below 22%, is discharged to a waste dump; while the ore is loaded and hauled to a primary gyratory crusher (see Fig. 1). Depending on its iron content, the crushed ore is separated into middlings and rich fraction. These two ore fractions are then sent to the beneficiation plant in which they go through two different processing routes: on the one hand, middlings are processed through dense media separation, magnetic separation, optical sorting and finally screening/secondary crushing; on the other hand, the rich fraction is only processed through screening/secondary crushing. This results in a concentrate with an average iron content of 33.5%. The

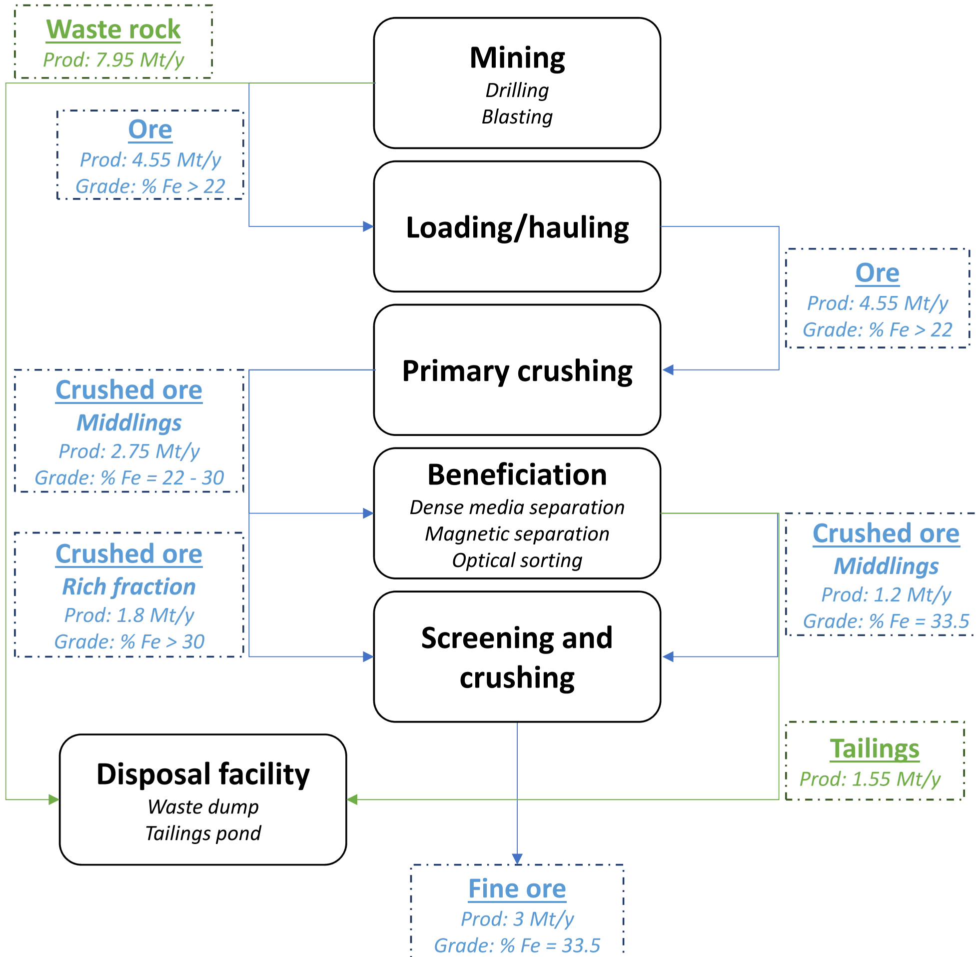

Fig. 1. Flowsheet of the Erzberg process.

beneficiation stage also generates tailings which are either disposed of to a waste dump (coarse tailings) or in dams (fine tailings).

2.2. Lujar mine

The Lujar mine is a small underground mine located in Orgiva (Spain). The deposit is mainly comprised of fluorspar with an average content of 35% in the ore and, in a lower extent, galena (PbS) with an average content of 2% in the ore. The latter mineral is however not exploited for now. Annually, the mine produces about 10 kilotons of fluorspar concentrates with different grades intended to different industries: metallurgical (% $CaF_2 > 70\%$) and cement (% CaF_2: 35%–50%) grades. Regarding the processing of the ore, a cut-off grade is set around 35% CaF_2:

- The ore is processed when its fluorspar content exceeds 35%;
- The ore whose fluorspar content ranges from 10 to 35% is stored in chambers for potential future reuse;
- The ore with a fluorspar grade inferior to 10% is placed back into excavation voids for rehabilitation and construction purposes (backfilling).

Once mined, the high grade ore is loaded and hauled to the underground treatment plant in which it goes through a comminution stage (jaw crushing, screening) followed by a beneficiation stage including dense media separation, screening and gravity concentration in spirals (see Fig. 2). This leads to the production of different concentrates with different grades in terms of fluorspar. The final products are obtained after a final drying stage in order to remove the residual water. The beneficiation stage also leads to the generation of tailings which are subsequently placed back into excavation voids for backfilling. Tailings with a fluorspar grade above 10% are stored for future processing. It is to be noted that the values (production flow rates and fluorspar grades) shown in Fig. 2 are average values based on the total outputs of the mine.

2.1.3. Alternative mining solutions and associated scenarios

In parallel to the current mining operations implemented in the Erzberg and Lujar mines, two alternative solutions relative to blasting operations are considered, based on available data drawn from experimental tests: on the one hand, the use of alternative explosive compositions; and on the other hand, the implementation of a new blast design method, through the use of electronic detonators for initiating the explosive charges. The development of these alternative solutions targets two main objectives: i) to reduce the actual (i.e. direct) on-site environmental impacts induced by blasting operations, in particular airborne emissions and ground vibrations; ii) to improve the overall mining performance, especially regarding downstream operations such as crushing. In the following, two “alternative mining scenarios” are derived from these solutions:

- The first scenario aims at comparing different explosive compositions. In this respect, three alternative compositions are considered in this scenario: i) a pure emulsion (referred to as E682), ii) a blended emulsion composed of E682 and 30% ANFO (Ammonium Nitrate Fuel Oil), and iii) a blended emulsion composed of E682 and 5% aluminum. Tests on these compositions were carried out at

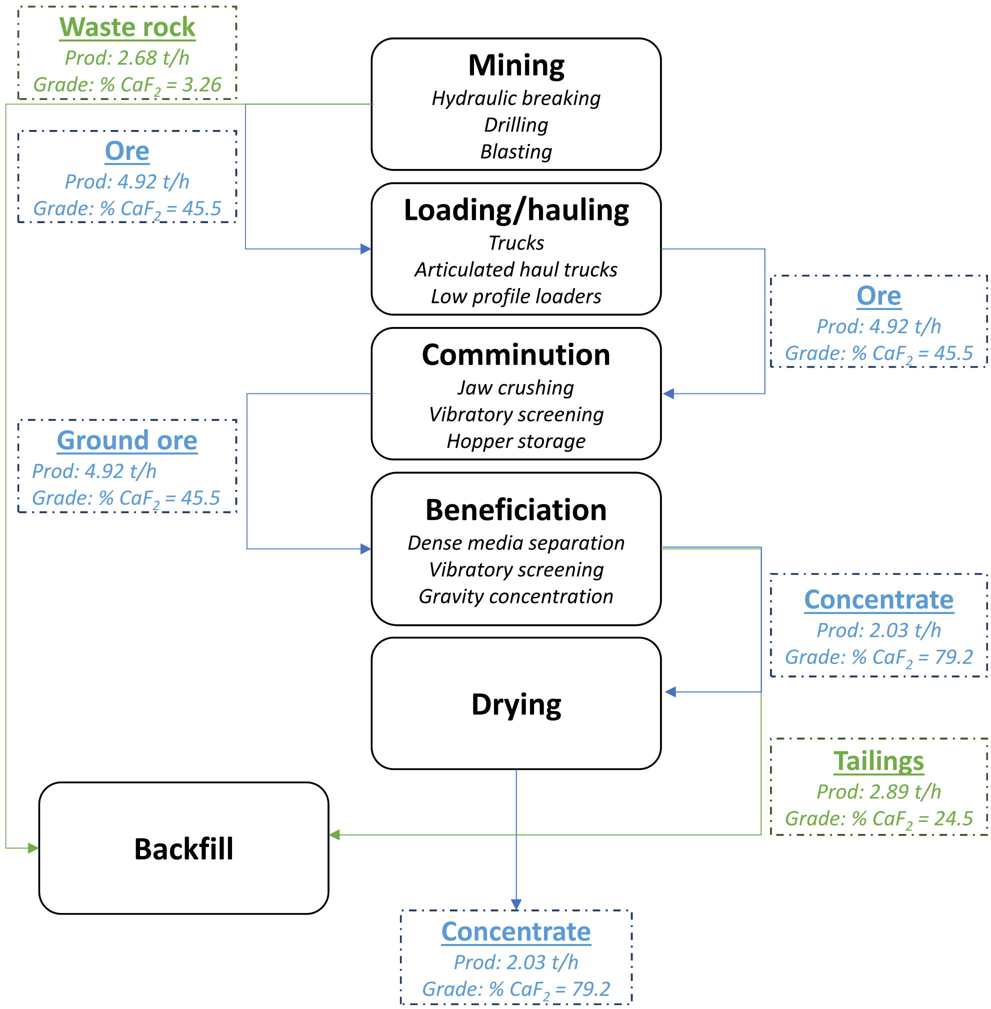

Fig. 2. Flowsheet of the Lujar process.

laboratory scale, through blasting trials in chambers, with the aim of measuring air emissions resulting from the blasting of the explosives. For comparison purposes, each explosive composition is assumed to be applied in the Erzberg mine, where blasting operations currently use ANFO as well as pure emulsions.

- The second scenario focuses on the implementation of a new blast design method, which primarily consists in a change of delay times (blasting in mining operations generally works by detonating loads of explosive charges placed in different blastholes with delays in milliseconds in the firing sequence). To proceed to these changes, electronic detonation systems were used thus allowing individual control of delay times for every single drillhole and a negligible time dispersion, as opposed to non-electric detonators used in traditional mining schemes, which apply fixed delay intervals and dispersion about the nominal delay, hence reducing the capacity of implementing changes. In this context, series of blasting trials were carried out on the Erzberg site, set with different delay times, firstly in order to observe whether this new blast design method can result in reduced ground vibrations (which may represent important local nuisances). Subsequently, potential improvements in the mining performance were investigated (e.g. regarding crushing operations), i.e. which influence vibration optimized blasting patterns have on rock fragmentation, therefore with potential influence on the environmental performance of the plant.

2.2. *Goal and scope definition*

This LCA study aims at assessing the cradle-to-gate environmental impacts of the exploitation of the two mineral deposits in a life cycle perspective. The objective is twofold:

i) The assessment of the environmental impacts of iron and fluorspar mining, respectively in the Erzberg and Lujar mines, so as to identify the main environmental hotspots associated with these operations in a business-as-usual functioning. In the following, these operations are reflected through two “reference scenarios”.

ii) The assessment of the environmental impacts of iron ore mining, in the Erzberg mine, resulting from the implementation of alternative mining solutions (i.e. alternative explosive compositions and new blast design method), reflected through the two previously defined “alternative scenarios”, so as to assess potential environmental benefits or burden-shifts associated with these solutions.

Two functional units (FU) are distinguished, as a function of each site under study; respectively, “the production of one ton of iron concentrate, with a Fe-content of 33.5%”, and “the production of one ton of fluorspar concentrate, with an average CaF_2 content of 79.2%”. These FU, with different degrees of purity for each concentrate, imply different levels of efforts (e.g. in terms of electricity consumption) in the ore processing stages (e.g. concentration) but also subsequently in the downstream refining stages (out of the scope of this cradle-to-gate study, which focuses on the mining processes).

The system boundaries include i) the direct emissions to environment generated by the mining operations from ore to concentrate; ii) the direct resource extractions and uses from the mining and concentration operations; iii) the production and supply of ancillary materials and energy; and iv) the infrastructure and equipment associated with each mine site.

The environmental impacts are calculated by use of the Simapro LCA software (version 9.0), considering the European EF (Environmental Footprint) life cycle impact assessment method (EF method 2.0; Fazio et al., 2018) as implemented in the software. The EF method encompasses a total of 16 impact categories whose models are recommended by the Joint Research Center (JRC) of the EC in the context of the European Product and Organization Environmental Footprint, which seeks to establish a common method to measure and communicate the life cycle environmental performance of products and organizations at the EU level.

2.3. Data inventories associated with the scenarios

The foreground system stands for all the processes for which specific data have been obtained and used in the modelling. The background system, i.e. all the processes upstream and downstream the process chains under study, e.g. electricity generation or ancillary materials production, is modelled by use of data drawn from the ecoinvent v3.5 database (Weidema et al., 2013; Ecoinvent centre, 2019).

2.3.1. Data relative to the Erzberg reference scenario

The data relative to the "Erzberg reference scenario", from the mining of the iron ore to the final production of a concentrate (fine ore product) with an iron content of 33.5% (see Fig. 1) are essentially primary on-site data provided by VA Erzberg GmbH, completed with data from other sources in the case of data gaps. For confidentiality reasons, the data inventory is provided as elementary flows only (see Supporting Information document 1) derived from the data provided by VA Erzberg GmbH by use of the Simapro software and ecoinvent v3.5 as the background database. The primary data encompass:

- Electricity consumption

Electricity, supplied from the grid (Austrian mix), is consumed by the equipment in the primary crushing, beneficiation and thickening stages.

- Diesel consumption

Diesel is used to fuel the machinery necessary for drilling, and loading/hauling the extracted ore.

- Ancillary materials

Include the explosives used for blasting, the steel consumed due to abrasion of the crusher wear parts, and the use of ferrosilicon in the beneficiation stage. Regarding the explosives (primarily emulsions and ANFOs), data about their consumption are provided by VA Erzberg GmbH, while data about their manufacture partly come from the manufacturer Maxam (ANFO composition, electricity consumption for explosives manufacture), completed with data drawn from Ferreira et al. (2015; emulsion composition). In terms of steel consumption, no estimation was available at Erzberg; therefore a proxy was considered based on the steel consumption relative to the crusher used in the Lujar mine (which may, however, imply some uncertainties due to the different characteristics of the run-of-mine in terms of abrasiveness and strength, and the different sizes of operations of each mine).

- Water balance

Includes, on the one hand, the water consumed in the beneficiation stage (drawn from a natural lake located near the mine), and on the other hand, the water released (to the same lake) after dewatering both produced concentrate and tailings.

- Emissions to water

Include the chemical substances (e.g. chloride, nitrate, sulfate, etc.) as well as the metallic elements (e.g. aluminium, copper, etc.) in the water discharged to the lake in compliance with the local regulations. This water composition is based on laboratory analysis of the water carried out by VA Erzberg GmbH. Moreover, nitrates are also considered to be emitted to groundwater, as these compounds are leached from the explosives used for blasting. Given that no on-site measurements of nitrates leaching were available, a 1% value of the nitrogen contained in the explosives was assumed to be leached to groundwater as nitrates in this study, based on an expert judgement from the explosive manufacturer, supported by estimates drawn from literature (estimates ranging from 0.2% (Ferguson and Leask, 1988) up to 28% (Morin and Hutt, 2008) of the nitrogen content within the explosives). Finally, regarding the tailings management in dams, it is assumed in this case that no emissions of metals or other pollutants to water systems occur given the ore mineralogy which is essentially composed of carbonates (i.e. non-sulfidic) and considering that protective measures prevent leaching to the environment. In particular, this assumption is in line with the modelling of non-sulfidic tailings disposal in the ecoinvent database, which considers no emissions to the environment.

- Emissions to air

Include detonation fumes, resulting from blasting (in particular from the explosives), and dust emitted in the mining, crushing and waste disposal steps. The detonation fumes are primarily composed of CO_2, NH_3, CO, SOx and NOx, according to calculations from the explosive manufacturer.

- Infrastructure and equipment

Include all the infrastructure (buildings, etc.) and equipment/machinery (excavators, drills, crushers, etc.) used on the mine site, adapted from data drawn from ecoinvent v3.5.

- Land occupation

Covers the information relative to land occupation and transformation by the mine site and the waste (tailings + waste rock) disposal facility.

2.3.2. Data relative to the Lujar reference scenario

The data relative to the "Lujar reference scenario", which includes all the unit operations from the mining of the fluorspar ore to the final production of a concentrate with an average fluorspar content of 79.2% (see Fig. 2), are essentially primary on-site data provided by the Minera de Orgiva, S.L. company. These data are completed with data from other sources in the case of data gaps. The data encompass (see Table 1 for an overview of the data inventory and Supporting Information document 2 for the full inventory):

- Diesel and electricity consumption

Diesel is used to fuel the machinery necessary for drilling and loading/hauling the extracted ore as well as for producing all the electricity necessary to power the mine site through on-site diesel generators. In particular, electricity is consumed to power the plant and the equipment used in the mining, comminution, beneficiation and drying steps. Regarding this last step, it is noteworthy that the dryers are only used in specific moments (during production peaks or raining periods),

Table 1
Overview of the data inventory relative to the Lujar mining operations.

Data	Value for 1 ton concentrate (FU)	Unit	Corresponding unit operation(s)
Inputs			
Diesel for machinery	338	MJ	Mining
	448	MJ	Loading/hauling
Electricity consumption	116	kWh	Mining
	57.2	kWh	Comminution
	53.4	kWh	Beneficiation
	16.6	kWh	Drying
Explosives (ANFO)	0.6	kg	Mining
Explosives (Dynamite)	0.2	kg	Mining
Ferrosilicon (FeSi)	1.4	kg	Beneficiation
Steel	0.08	kg	Mining
	0.6	kg	Comminution
	0.2	kg	Beneficiation
Water	123	L	Mining
	113	L	Beneficiation
Outputs			
Diesel losses (to soil)	0.06	kg	Loading/hauling

as part of the material is either dried with the heat generated by the power generators or naturally dried.

- Ancillary materials

Include the explosives used for blasting (primarily ANFO and dynamite), the steel consumed due to abrasion of the equipment (mainly in crushers, hoppers and mining machinery) and the use of ferrosilicon in the beneficiation stage. Regarding the explosives, data about their consumption is provided by the Minera de Orgiva company, while data about their composition and manufacture come from the manufacturer Maxam.

- Water balance

Includes all the water inputs from different sources (e.g. precipitations, tank supply truck) in the mining and beneficiation steps, as well as the water evaporation in the drying step. It is to be noted that these values express actual water inputs and outputs, and do not include the internal water recirculation.

- Emissions to air and water

Given the ore treatment goes through a wet process in an underground plant (in a chamber inside the mine), it is assumed that the dust and the detonation fumes generated throughout the ore mining and processing operations remain in the underground galleries (the dust is actually retrieved through a ventilation system and stored in silos). Accordingly, no emissions to air are considered in this case. Similarly, nitrates emissions to water are not considered either in this case, as it is observed there is no water system in the immediate surroundings of the mine (the aquifer is about 700 m beneath the mine, therefore it is assumed out of reach from any nitrates leakage). Regarding tailings management, it is assumed in this case that no emissions to water systems occur as these tailings are placed back into excavation voids (backfilling).

- Emissions to soil

Consider the diesel losses resulting from the machinery used for loading and hauling the extracted ore.

- Infrastructure and equipment

Include all the infrastructure (buildings, etc.) and equipment/machinery (excavators, drills, crushers, etc.) used on the mine site, adapted from data drawn from ecoinvent v3.5.

- Land occupation

Covers the information relative to the superficial land occupation and transformation by the mine site (mostly offices, garages, storage, etc.).

2.3.3. Data relative to the alternative scenario 1

The alternative scenario 1 refers to the hypothetical implementation of alternative explosive compositions in the context of the Erzberg mine, i.e. pure emulsion (E682) and blended emulsions, including the air emissions associated with these compositions. These alternative compositions are provided in Supporting Information document 3. In the absence of specific data relative to energy consumption, the energy necessary for the production of these emulsions is assumed to be equivalent to that necessary for the production of emulsion in the Erzberg reference scenario. In each composition, the alternative emulsions are considered to be implemented as a substitute for the pure emulsion currently used in Erzberg.

Moreover, the emissions of CO and NOx resulting from the blasting of the explosives have been measured at laboratory scale, through blasting trials in chambers (Table 2). These alternative emission factors are considered with respect to the different alternative explosive compositions, as substitutes for the corresponding emission factors used in the Erzberg reference scenario.

2.3.4. Data relative to the alternative scenario 2

The alternative scenario 2 refers to the implementation of a new blast design method, primarily through the change of delay times in the blasting step, by use of electronic detonation systems instead of non-electric ones. On-site blasting trials were carried out in the Erzberg mine, considering different delay times (four in total). To assess how this new blast design method may influence the mining performance, in particular the primary crushing operation, data about the electricity consumption of the crusher were measured so as to derive values in kWh of electricity consumed per ton of ore crushed (personal communication with Philipp Hartlieb, 2020). The electricity consumption values, measured as functions of the four delay times used in the blasting trials, are provided in Supporting Information document 3 (here expressed with respect to the value considered in the Erzberg reference scenario; while the delay times are not expressed for confidentiality reasons). For the comparison of environmental impacts between the Erzberg reference scenario and this alternative scenario, four averaged values of electricity consumption at primary crushing, as a function of each delay time, are considered.

3. Results and discussion

3.1. Environmental impacts of the reference mining scenarios and contribution analysis

3.1.1. Erzberg mine

In a life cycle perspective, the production of 1 ton of iron concentrate with an iron content of 33.5% at Erzberg potentially induces a total of

Table 2
Measured emissions of CO and NOx from the alternative explosives considered in scenario 1, as derived from López et al. (2018) and Nyberg et al. (2017).

	CO	NOx
Explosives	kg/kg explosive	kg/kg explosive
ANFO	0.025	0.018
Pure emulsion (E682)	0.0096	0.0018
Blended emulsion: E682 with 30% ANFO	0.018	0.0092
E682 with 5% aluminium	0.0075	0.0092

8.75 kg CO_2-eq (climate change) and 0.0191 kg N-eq (eutrophication marine). The complete list of impacts, considering the 16 categories of the EF method 2.0, is provided in Table 3.

Overall, the concentration step stands out as the main contributor to most of the impact categories considered (9 out of 16): climate change, ionizing radiation, photochemical ozone formation, respiratory inorganics, non-cancer human health effects, acidification terrestrial and freshwater, eutrophication freshwater, water scarcity and resource use - energy carriers (Fig. 3). Regarding these nine impact categories, the concentration step accounts for 40–78% of the impacts. Moreover, it also appears as a major contributor to impacts on ozone depletion, cancer human health effects, eutrophication marine, eutrophication terrestrial, and ecotoxicity freshwater (second contributor, with 30–42% of the impacts). The concentration step is overall a hotspot for 14 impact categories out of the 16 under study.

Furthermore, regarding 7 impact categories, namely ozone depletion, eutrophication marine, eutrophication terrestrial, cancer human health effects, ecotoxicity freshwater, land use and resource use - mineral and metals, the main contributions are shared among different process steps. Firstly, the loading and hauling step represents the main contribution to the ozone depletion, eutrophication marine and eutrophication terrestrial impact categories (46–49% of the impacts). Loading and hauling is also the second contributor in terms of climate change, photochemical ozone formation, respiratory inorganics, acidification terrestrial and freshwater, and resource use - energy carriers (16–41% of the impacts).

Secondly, the primary crushing step accounts for the largest share of the impacts in terms of cancer human health effects and ecotoxicity freshwater with respectively 62 and 43% of the impacts. It also appears as the second contributor to the non-cancer human health effects and resource use - mineral and metals impact categories (respectively 34 and 18% of the impacts).

Finally, the mining step significantly contributes to the land use and resource use - mineral and metals impact categories but has limited contributions regarding the other categories (less than 10%); while the waste/tailings disposal step solely contributes to the land use impact category. Similarly, the dewatering step is the second contributor to the ionizing radiation impact category but only represents a slight share of the impacts regarding all the other categories (less than 11%).

Over the entire Erzberg process chain, the use of chemicals and ancillary materials stands for the main environmental hotspot as their use induces the largest share of the impacts regarding 10 out of the 16 impact categories considered in this study (39–90% of the impacts; Fig. 4), encompassing the impact categories respectively dominated by the concentration (8 categories excepting ionizing radiation) and the primary crushing (2 categories) steps. In particular, these impacts are primarily driven by the use of ferrosilicon (FeSi) in the concentration step, except for the toxicity-related impact categories (human health effects and ecotoxicity) for which the impacts are primarily driven by the use of steel as grinding media in the primary crushing step, and to a lower extent, in the concentration step. It is however to be noted that the steel consumption value considered in this case is drawn from the Lujar data, in the absence of specific data relative to the Erzberg situation, which may therefore imply some uncertainties.

Diesel combustion in machinery is also responsible for significant environmental impacts regarding 9 impacts categories: ozone depletion, eutrophication marine and eutrophication terrestrial, for which diesel accounts for the largest share of the impacts (48–50%, essentially due to NOx emissions to air); climate change, ionizing radiation, photochemical ozone formation, respiratory inorganics, acidification terrestrial and freshwater, and resource use - energy carriers, for which it represents a major contributor to the impacts (17–42%). In particular, diesel appears as the main driver of the environmental impacts induced by the loading and hauling step.

Direct exchanges from/to the environment (in the foreground system) also stand out for some impact categories: land use, due to the transformation and occupation of the land both by the mine and waste disposal sites; water scarcity, due to water inputs from the lake; and resource use - mineral and metals, due to the extraction of the iron resource from the ground.

On the contrary, electricity consumption only accounts for a slight share (less than 10%) of the impacts with respect to all categories excepting ionizing radiation (main contributor with 45% of the impacts), eutrophication freshwater and climate change (respectively 18 and 13% of the impacts). The use of explosives for blasting as well as the mine infrastructure/equipment only account for limited environmental impacts considering all impacts categories. Finally the direct emissions to environment other than those from diesel combustion (e.g. nitrates to groundwater and NOx emissions to air from blasting) only contribute to a very slight extent (3–8%) to a few impact categories (eutrophication and acidification).

Table 3
Environmental impacts induced by the production of 1 ton of iron concentrate (33.5% Fe) at Erzberg, considering 16 impact categories from the EF method 2.0

Impact categories	Unit	Values
Climate change	kg CO_2 eq	8.75
Ozone depletion	kg CFC11 eq	9.43E-07
Ionizing radiation	kBq U-235 eq	0.61
Photochemical ozone formation	kg NMVOC eq	0.068
Respiratory inorganics	disease inc.	1.40E-06
Non-cancer human health effects	CTUh	1.42E-06
Cancer human health effects	CTUh	3.34E-07
Acidification terrestrial and freshwater	mol H^+ eq	0.063
Eutrophication freshwater	kg P eq	7.71E-03
Eutrophication marine	kg N eq	0.0191
Eutrophication terrestrial	mol N eq	0.218
Ecotoxicity freshwater	CTUe	5.96
Land use	Pt	266
Water scarcity	m^3 depriv.	1.91
Resource use, energy carriers	MJ	180
Resource use, mineral and metals	kg Sb eq	4.98E-05

3.1.2. Lujar mine

In a life cycle perspective, the production of 1 ton of fluorspar concentrate with a fluorspar content of 79.2% at Lujar potentially induces a total of 174 kg CO_2-eq (climate change), 0.56 kg N-eq (eutrophication marine). The complete list of impacts, considering the 16 categories of the EF method 2.0, is provided in Table 4.

Overall, the mining step stands out as the main environmental hotspot with respect to all impact categories considered in this study except for the eutrophication freshwater category for which mining represents the second largest contribution (Fig. 5). In particular, the mining step accounts for 41–44% of the impacts with respect to 10 categories: climate change, ozone depletion, ionizing radiation, photochemical ozone formation, respiratory inorganics, acidification terrestrial and freshwater, eutrophication marine, eutrophication terrestrial, water scarcity and resource use - energy carriers. Regarding the other impact categories, it contributes to 21–32% of the total impacts.

Furthermore, the loading and hauling step also represents a major contributor to the environmental impacts as it contributes to more than 17% of the impacts with respect to all categories. In particular, it accounts for more than 25% (up to 41%) of the impacts in terms of climate change, ozone depletion, ionizing radiation, photochemical ozone formation, respiratory inorganics, acidification terrestrial and freshwater, eutrophication marine, eutrophication terrestrial and resource use - energy carriers.

Moreover, the concentration step accounts for 9–32% of the impacts regarding all categories, with more significant contributions in terms of non-cancer human health effects, eutrophication freshwater, land use and water scarcity (more than 20% of the total impacts). Similarly, the comminution step also accounts for 9–26% of the impacts regarding all categories excepting the respiratory inorganics category, with more

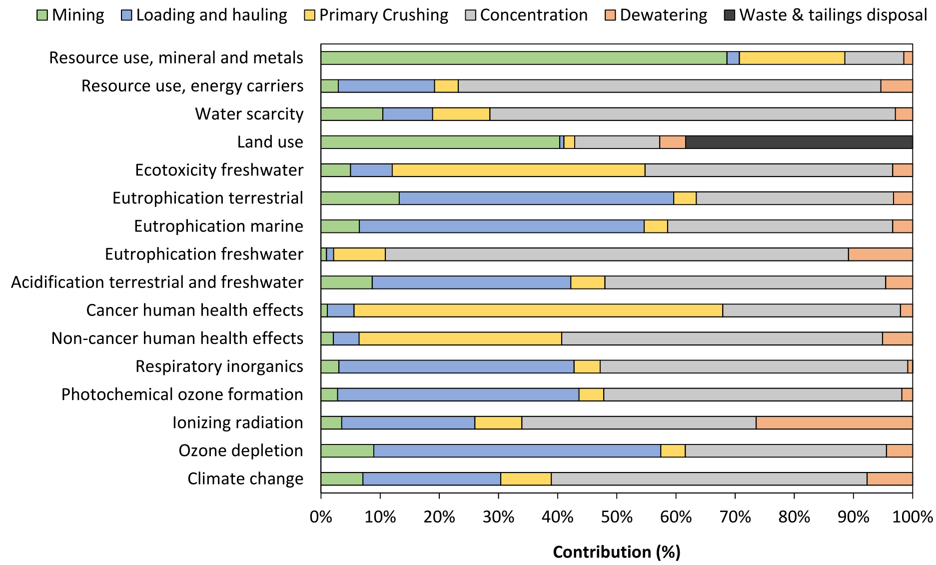

Fig. 3. Environmental impacts of iron concentrate production at Erzberg – contributions by unit operations, considering 16 impact categories from the EF method 2.0.

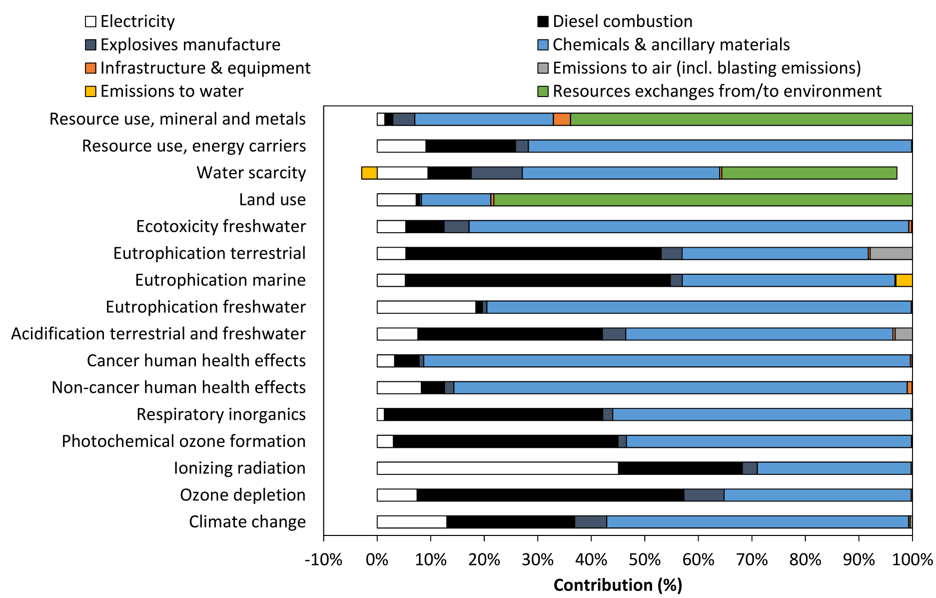

Fig. 4. Environmental impacts of iron concentrate production at Erzberg – contributions by types of exchanges with technosphere/environment, considering 16 impact categories from the EF method 2.0.

important contributions to the non-cancer and cancer human health effects and resource use - mineral and metals impact categories.

As for the drying step, the latter accounts for relatively limited impacts with respect to most impact categories excepting non-cancer human health effects, eutrophication freshwater, land use and resource use - mineral and metals for which it accounts for more than 10% of the impacts.

Over the entire Lujar process chain, two major environmental hotspots are identified: the use of diesel and the mine infrastructure/equipment. In these operations, diesel is consumed to fuel the machinery (e.g. loaders, dumpers), and also to produce electricity through on-site generators (Fig. 6). The total use of diesel dominates the impacts of 11 categories out of 16. In particular, the use of diesel in the machinery, respectively in the loading/hauling as well as the mining steps, is responsible for the largest share of the impacts in terms of photochemical ozone formation, respiratory organics, acidification terrestrial and freshwater, eutrophication marine/terrestrial with contributions varying from 51 to 79%; while the use of diesel for electricity production, primarily in the mining step and in a lower extent in the comminution, concentration and drying steps, accounts for the main contributions to the climate change, ozone depletion, ionizing radiation, cancer human health effects, water scarcity, and resource use - energy carriers impact categories (28–49% of the impacts).

Regarding the mine infrastructure/equipment, the latter represents the largest share of the impacts in terms of non-cancer human health effects, eutrophication freshwater, land use and resource use - mineral and metals. It is however to be noted that, as mentioned in the data inventory section (2.3.2), the modelling of this infrastructure/equipment relies on data drawn from ecoinvent v3.5, which may not be totally representative of the actual infrastructure/equipment of the Lujar mine. Moreover, while the mining operator may control its on-site diesel consumption and accordingly its associated impacts, the impacts

Table 4
Environmental impacts induced by the production of 1 ton of fluorspar concentrate (79.2% CaF_2) at Lujar, considering 16 impact categories from the EF method 2.0

Impact categories	Unit	Values
Climate change	kg CO_2 eq	174
Ozone depletion	kg CFC11 eq	3.64E-05
Ionizing radiation	kBq U-235 eq	11.7
Photochemical ozone formation	kg NMVOC eq	1.69
Respiratory inorganics	disease inc.	2.9E-05
Non-cancer human health effects	CTUh	1.58E-05
Cancer human health effects	CTUh	2.27E-06
Acidification terrestrial and freshwater	mol H^+ eq	1.48
Eutrophication freshwater	kg P eq	0.041
Eutrophication marine	kg N eq	0.56
Eutrophication terrestrial	mol N eq	6.10
Ecotoxicity freshwater	CTUe	65.0
Land use	Pt	1132
Water scarcity	m^3 depriv.	21.3
Resource use, energy carriers	MJ	2516
Resource use, mineral and metals	kg Sb eq	0.00075

associated with the infrastructure and equipment are rather generated upstream along supply chains (e.g. in the production of materials composing the equipment), where the mining operator hardly has any influence.

Finally, the use of chemicals and ancillary materials (in particular, steel in the comminution step and ferrosilicon in the concentration step) contributes to some extent to the non-cancer and cancer human health effects as well as the eutrophication and ecotoxicity freshwater impacts (up to 23% of the impacts), but have relatively limited impacts considering the other categories. The exchanges with the environment (i.e. in the Lujar case, emissions to soil and resources from the environment) have a relatively important contribution to the water scarcity impacts (due to water inputs) but have nearly no contributions to the other impact categories. Similarly, the environmental impacts induced by the use of explosives also appear very limited.

3.2. Scenarios comparison: reference vs alternative scenarios

3.2.1. Change of explosives composition and associated emissions

The three alternative compositions of explosives considered in scenario 1, combined with measurements of emissions to air resulting from their blasting (CO and NOx), overall induce larger environmental impacts than those calculated for the Erzberg reference scenario, but in a very limited extent (less than 3%).

However, the use of the three alternative explosives induces a relatively important increase in impacts when only focusing on the mining step, excepting for the ozone depletion impact category for which a significant decrease in impacts (29%–32%) is observed (Fig. 7). Regarding the use of pure E682 and E682 blended with 30% ANFO, the increase in impacts is below 10% for 12 impact categories, but in the meantime ranges from 10% to 21% for the three remaining impact categories: eutrophication terrestrial, acidification terrestrial and freshwater, eutrophication marine (E682 only) and photochemical ozone formation (E682 + 30% ANFO). The increase in impacts is larger regarding the use of E682 with 5% aluminium, ranging from 14% to 114% with respect to 9 impact categories: the 4 previously mentioned along with ionizing radiation, cancer and non-cancer human health effects, ecotoxicity freshwater and eutrophication freshwater.

In three cases of impact categories (eutrophication terrestrial, acidification terrestrial and freshwater, and photochemical ozone formation), the larger impact is mainly driven by the larger emission factors considered for CO and NOx from blasting. For example, the larger emission factor associated with NOx induces approximately 90% of the increase in impacts with respect to eutrophication terrestrial. On the contrary, regarding most other impact categories, the larger impacts of the alternative explosives are essentially driven by their more impacting manufacture.

3.2.2. New blast design method implementation

The implementation of the new blast design method, through the change of delay times in the blasting step, overall does not significantly affect the environmental impacts of the Erzberg mining operations (less than 1% decrease in impacts in comparison with the reference scenario).

When exclusively focusing on the primary crushing step, the change of delays only marginally affects the impacts (less than 0.5% reduction in impacts) regarding five impact categories: respiratory inorganics, non-cancer and cancer human health effects, ecotoxicity freshwater and resource use - mineral and metals. As for the other impact categories considered in this study (Fig. 8), the decrease in impacts varies from 2% (photochemical ozone formation) up to 8% (resource use – energy carriers) with respect to the reference Erzberg scenario, excepting in terms

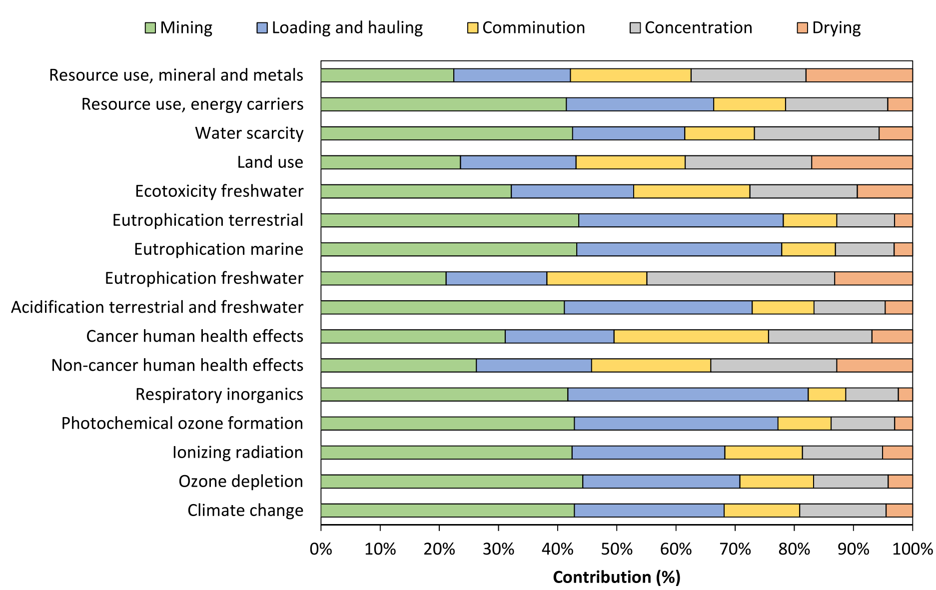

Fig. 5. Environmental impacts of fluorspar concentrate production at Lujar – contributions by unit operations, considering 16 impact categories from the EF method 2.0.

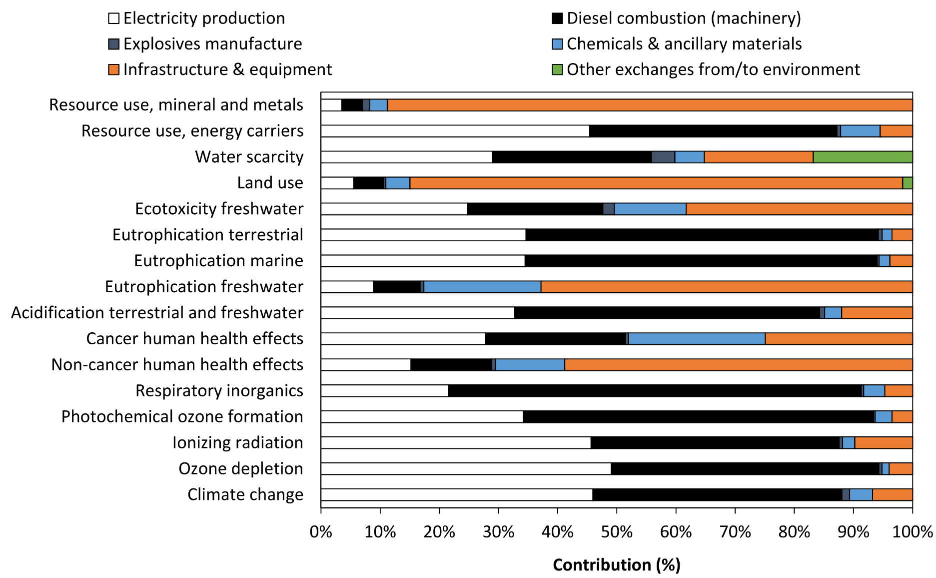

Fig. 6. Environmental impacts of fluorspar concentrate production at Lujar – contributions by types of exchanges with technosphere/environment, considering 16 impact categories from the EF method 2.0.

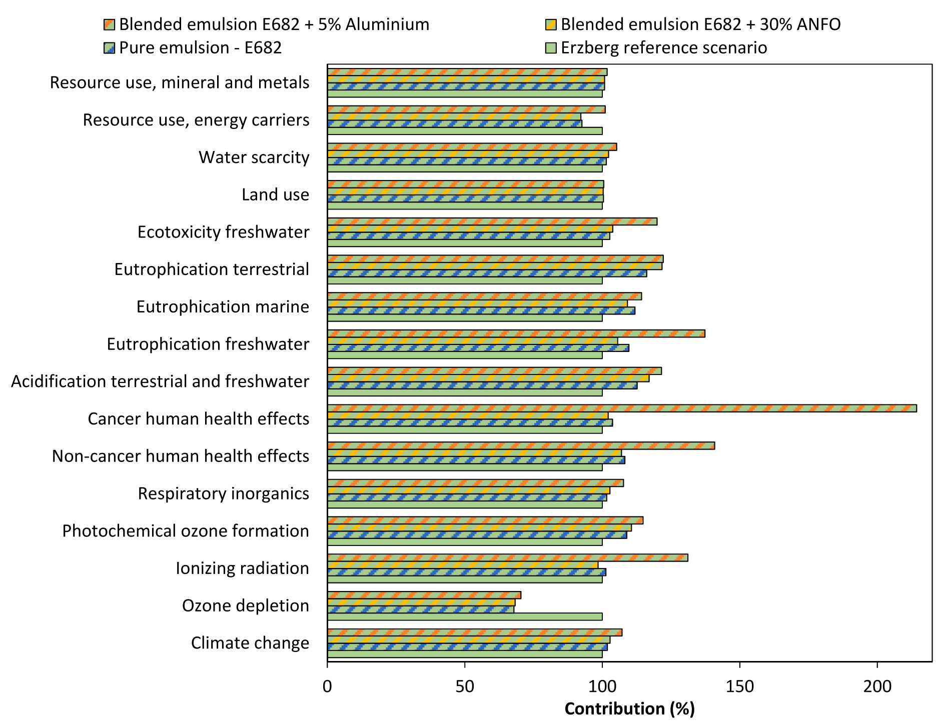

Fig. 7. Environmental impacts of the mining step at Erzberg – comparison of alternative explosive compositions and their associated air emissions with the reference scenario (set to 100%), considering 16 impact categories from the EF method 2.0.

of ionizing radiation and land use, for which the reduction in impacts appears to be larger, respectively reaching 20% and 14% (considering delay 1).

3.3. Environmental performance of the Erzberg and Lujar mining operations: sensitivity analysis

3.3.1. Sensitivity to nitrates leaching from explosives

Nitrates leaching from ammonium nitrates-based explosives (e.g. ANFO, emulsion, etc.) is a well-known phenomenon in the mining industry. Such leaching may affect and contaminate surrounding water systems, in particular groundwater. As described in the inventory section relative to Erzberg (2.3.1), 1% of the nitrogen content within the explosives was assumed to be leached to groundwater in the form of nitrates, based on an expert judgement supported by literature data. However, this 1% value may be considered as a conservative value in comparison with the estimates drawn from literature (0.2 up to 28%). Indeed, while emissions of nitrates to groundwater do not appear to significantly contribute to the overall life cycle environmental impacts of the Erzberg process chain when considering a 1% value (Fig. 4); when considering the upper bound of nitrates leaching value provided by the literature, i.e. 28%, the impacts over the entire Erzberg process chain show a 77% increase in terms of eutrophication marine (while other impact categories are not affected by a change of nitrates emissions

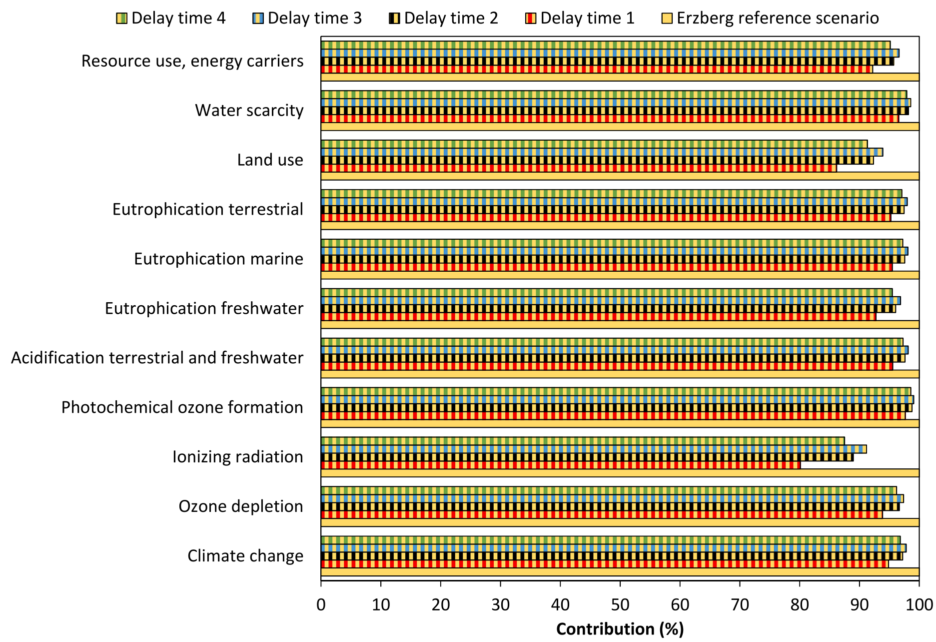

Fig. 8. Environmental impacts of the primary crushing operation at Erzberg, as functions of different delay times set in the blasting step and compared with the reference scenario (set to 100%), considering 11 impact categories from the EF method 2.0.

value given the absence of characterization factors associated with nitrates emissions to groundwater). In that case, such a discrepancy highlights that the environmental performance of mining operations may be very sensitive to the amount of nitrates emitted to groundwater from the explosives, and emphasizes the need for accurate on-site measurements of these leakages.

3.3.2. *Sensitivity to electricity supply*

While electricity does not significantly contribute to the environmental impacts in the Erzberg case, it stands for an environmental hotspot in the Lujar case. Fig. 9 compares the environmental impacts of the Lujar mining operations as functions of different sources of electricity supply, namely electricity from the Spanish grid mix and electricity from the grid entirely supplied from renewable sources (on the one hand, photovoltaic power station and on the other hand, wind turbine), with the reference scenario. Data regarding the electricity production from these different sources are drawn from the ecoinvent v3.5 database. Depending on the sources of electricity supply, important discrepancies can be observed in terms of life cycle environmental

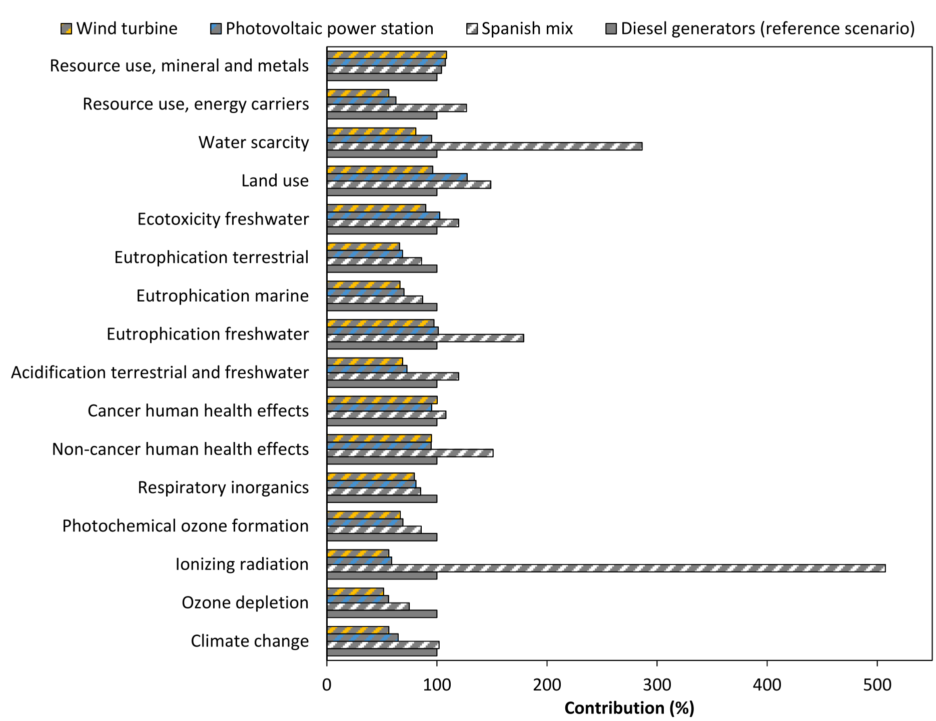

Fig. 9. Environmental impacts of the Lujar mining operations, as functions of different sources of electricity supply compared with the reference scenario (set to 100%), considering 16 impact categories from the EF method 2.0.

impacts. Indeed, on the one hand, the consumption of electricity from the Spanish mix increases the impacts with respect to 11 categories out of 16, primarily driven by the share of fossil (hard coal and oil in a lower extent) and nuclear sources in the mix: climate change (+2%), ionizing radiation (+407%), non-cancer and cancer human health effects (respectively +51% and +8%), acidification terrestrial and freshwater (+20%), eutrophication freshwater (+79%), ecotoxicity freshwater (+20%), land use (+49%), water scarcity (+186%) and resource use – energy carriers and mineral/metals use (respectively +27% and +4%). Regarding the five remaining impact categories, the Spanish mix leads to a decrease in impacts ranging from 13% to 25%. On the other hand, the consumption of electricity from renewable sources overall enables a reduction in impacts regarding most impact categories considered (respectively 12 and 14 categories for the photovoltaic power station and the wind turbine scenarios, with 4 up to 49% of reduction in impacts), except for a few categories: cancer human health effects (+0.2% impacts for wind turbine), eutrophication freshwater, ecotoxicity freshwater, land use (1–28% increase in impacts for the photovoltaic power station) and resource use – mineral and metals (8–9% increase in impacts for both renewable sources). These results highlight that the environmental performance of mining operations may be very sensitive to the source of electricity supply, and that renewable energies overall appear as promising alternatives towards mitigating their associated environmental impacts.

3.4. Positioning of this study with respect to the state-of-the-art

3.4.1. Positioning with respect to ecoinvent

In comparison with the data relative to iron (Classen et al., 2009) and fluorspar (Jungbluth et al., 2009) concentrates production available in the widely used ecoinvent database (in its 3.5 version), the two mining case studies considered in this study offer relatively different insights. Firstly, the products considered in ecoinvent differ from those of the Erzberg and Lujar mines in terms of purity, as ecoinvent respectively considers an iron concentrate with a 65% Fe content (33.5% Fe in the Erzberg concentrate) and a fluorspar concentrate with a 97% CaF_2 content (79.2% CaF_2 in the Lujar concentrate). These different degrees of purity in the concentrates therefore imply different functional units between the ecoinvent database and this study. Moreover, the ore grades considered in ecoinvent also differ from those of this study: 46% Fe in the ecoinvent iron ore (from 22% up to more than 30% Fe in Erzberg) and 92% CaF_2 in the ecoinvent fluorspar ore (45.5% CaF_2 in Lujar). Consequently, these different grades and purities imply different processing requirements, which translate in the data inventories, e.g. in terms of electricity, diesel, heat consumptions or emissions to the environment. It may be noted that these discrepancies in terms of purity imply different requirements, on the one hand, in the ore processing stages (e.g. concentration) in which a higher purity in the concentrate may require more processing efforts, on the other hand, in the downstream refining stages in which a higher purity in the concentrate may require less processing efforts. Therefore, one possibility for ensuring a fair comparison between concentrates with different degrees of purity could be to expand the system boundaries by including the downstream stages until the production of a refined product (which however are out of the scope of this study).

Secondly, in the case of fluorspar, significant differences can be observed between the process chains considered in ecoinvent and the Lujar mine (while for iron the process chains are relatively similar). Indeed, the Lujar mine exploits fluorspar through underground mining operations subsequently followed by gravity concentration, whereas ecoinvent only considers open-pit mining operations subsequently followed by flotation. These important differences in the modelling of iron and fluorspar concentrates production result in significant discrepancies in terms of impacts assessment results, with differentials amounting to several orders of magnitude between ecoinvent and this study (respectively 3 to 35 and 0.5 to 6 orders of magnitude for iron and fluorspar productions; Fig. 10).

3.4.2. Positioning with respect to scientific literature

The number of LCA studies specifically addressing the environmental impacts of iron and fluorspar mining overall appears relatively limited in the scientific literature. No studies were found to address fluorspar mining, while regarding iron ore mining only two studies were found (Table 5): on the one hand, Ferreira and Leite (2015) focused on the exploitation of iron ore (with an average Fe content of 43%) in an open-pit mine in Brazil, producing an iron concentrate as final product; on the other hand, Norgate and Haque (2010) considered the production of an iron ore (with an average Fe content of 60%) in an open-pit mine in Australia.

In terms of impact assessment, the climate change (GWP) impacts calculated from the Erzberg case study appear to be slightly lower than those calculated in these two studies. Other impact categories were not considered, as they were different from one study to the other. These discrepancies in impacts may in particular be explained by several differences in the respective product systems: i) in terms of ore/concentrate grade; ii) in terms of process chains (flotation is implemented in the Brazilian case; stacking/reclaiming, rail transport and port operations are considered in the Australian case); iii) electricity supply mix. These different product systems accordingly imply different processing requirements which ultimately result in various environmental hotspots that differ from those identified in the Erzberg case: electricity and grinding media in the Brazilian process (Ferreira and Leite, 2015), diesel for loading/hauling and electricity for crushing/screening in the Australian process (Norgate and Haque, 2010).

3.5. Limitations

3.5.1. Limitations relative to the impact assessment in this study

Different limits, to be considered when interpreting the impact assessment results, may be identified in this study. Firstly, the modelling of the background system is based on the ecoinvent database, which includes some uncertainties and approximations which may be more or less important depending on the considered dataset. Moreover, the correspondence between the foreground and the background data is sometimes relatively approximate, which ultimately contributes to the uncertainty of the results. For example, regarding the first alternative scenario (i.e. alternative explosive compositions), the modelling of the upstream manufacturing phase of the diverse explosives considered is based on specific composition data; while the inventories associated with the production of the compounds, and of the subsequent production of explosives, rely on rough proxies (drawn from ecoinvent and literature).

Secondly, the larger CO and NOx emissions considered for the three alternative explosives were obtained from a different procedure (measurements at laboratory scale) than in the reference scenario (calculations). Therefore, the larger emissions in this scenario may result from different estimation approaches rather than from actually lower emissions for the reference explosive compared to the alternative ones.

Finally, results regarding some impact categories should be considered with caution, as the underlying characterization models associated with several categories may show some limits e.g. regarding resource depletion or toxicity to humans and ecosystems (Santero and Hendry, 2016). For example, the impacts associated with resource use – mineral and metals are calculated based on the abiotic depletion potential (ADP) approach, which considers the depletion of a resource once it is extracted from the Earth's crust by accounting for the reduction of its geological stock. Accordingly, such an approach attributes most of the impacts in terms of resource depletion to the mining step, as it is responsible for the extraction of the resource (as e.g. observed in the Erzberg reference scenario). However, such a perspective may be seen rather limited, as the resource is not necessarily depleted right after its extraction, but rather remains in an "anthropogenic stock" (Berger et al.,

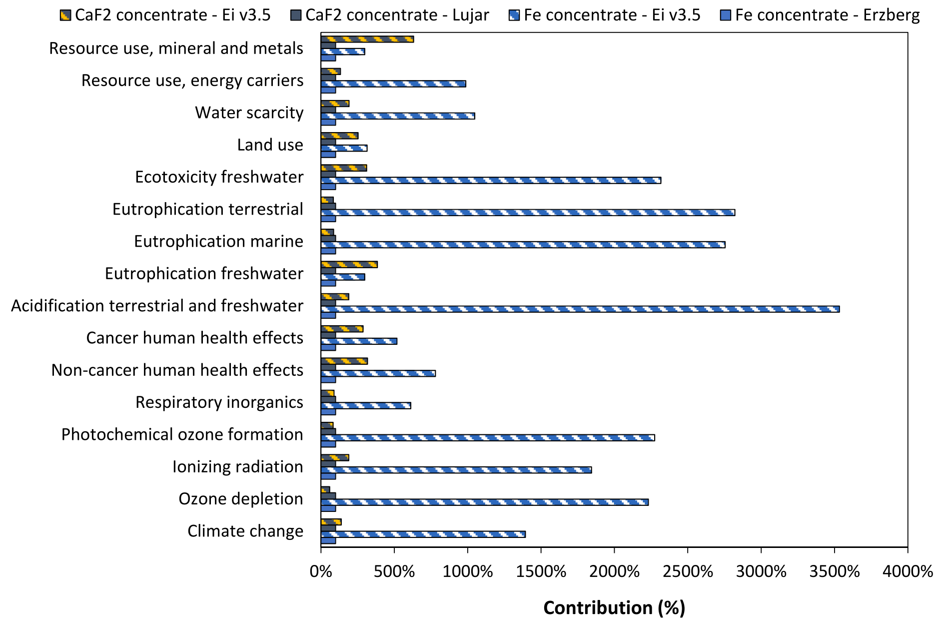

Fig. 10. Environmental impacts of iron and fluorspar concentrates production from the ecoinvent v3.5 database, respectively compared to the Erzberg and Lujar reference scenarios (set to 100%), considering 1 ton of concentrate (with different degrees of purity) and 16 impact categories from the EF method 2.0 (Ei = ecoinvent).

Table 5
Overview of studies addressing the environmental impacts of iron ore mining, including this study.

Study	Functional unit	Ore/ concentrate grade	Climate change (GWP) impacts (kg CO_2 eq)
Our study	"the production of one ton of iron concentrate, with a Fe-content of 33.5%"	>22% Fe (in ore) 33.5% Fe (in concentrate)	8.75
Ferreira and Leite (2015)	"one ton of iron ore concentrate at the gate"	43% Fe (in ore)	13.3
Norgate and Haque (2010)	"1 ton of ore or concentrate ready for ship loading"	60% Fe (in ore)	11.9

2020). In this context, approaches are currently under development to account for resource dissipation in LCA, focusing on the actual losses of resources along process and more generally life-cycle chains, rather than resource extraction, in order to support more resource-efficient solutions (Beylot et al., 2020a, 2020b). On another note, while most environmental impacts may be considered permanent, impacts in terms of land use may rather be considered temporary, as they reflect the use and occupation of the land over the period of activity of the mine. Once the activity ceases, these land use impacts may potentially be mitigated through mine closure practices (e.g. restoration, reclamation or rehabilitation; Limpitlaw and Briel, 2014).

3.5.2. Limitations relative to the impact assessment in the overall mining context

Mining operations, and in particular blasting operations, may be responsible for diverse impacts to the surrounding environment, e.g. ground vibrations, noise or dust. While some of these impacts are accounted for in the currently existing LCA characterization methods, others are not covered despite the important nuisances to the environment they may represent.

Regarding ground vibrations, to our knowledge, no characterization method nor LCA study accounts for such impacts, excepting one LCA study relative to the construction sector mentioning vibration effects, but without further quantification (Li et al., 2010). Outside the LCA field, Mirmohammadi et al. (2009) and Monjezi et al. (2009) assessed the effect of vibrations due to blasting operations on the environment through a semi-quantitative indicator called "impacting factor" based on the Folchi method (Folchi, 2003), by scoring the intensity of the underground vibrations. However, no attempts to implement such an indicator into the LCA framework were found to be made.

In terms of noise generation, different attempts to integrate this aspect into the LCA framework were made (Guinée et al., 1993; Lafleche and Sacchetto, 1997; Müller-Wenk, 2004). In this respect, one approach was to consider noise as an environmental externality in the assessment of a wind farm so as to monetize the impact and compare it to other environmental impacts (Schleisner, 2000). Considering another approach, Müller-Wenk (2004) proposed a method to assess the impacts on human health of traffic noise by measuring the impacts of noise on communication and sleep disturbances. However, despite these attempts, no approach to consider noise is currently implemented in LCAs of mining operations.

4. Conclusions

This study enabled the assessment of the environmental performance of mining operations through two case studies respectively considering the cradle-to-gate exploitation of iron ore deposits in the Erzberg open-pit mine, and of fluorspar deposits in the Lujar underground mine. In a life cycle perspective, the consumption of chemicals and ancillary materials, in the concentration (ferrosilicon) and comminution (steel) steps, as well as the consumption of diesel by the machinery necessary for loading/hauling the ore represent the main environmental hotspots regarding the Erzberg mining operations; while the consumption of diesel by the machinery and the on-site generators, especially in the mining and loading/hauling steps, along with the mine infrastructure/equipment stand for the main environmental hotspots regarding the Lujar mining operations.

The implementation of alternative mining solutions in the blasting step, consisting respectively in a change of explosive compositions (including their associated air emissions) and a change of detonation systems allowing a control of delay times, were shown to induce limited environmental effects to the Erzberg operations. However, when focusing on the mining step, the impacts relative to the blasting of the alternative explosives showed an increase regarding several impact categories. These differences in impacts between the reference and the alternative scenarios may nevertheless also result from inconsistencies in terms of LCA modelling and emissions measurements rather than from different environmental performances of the alternative scenarios (which may however exist). Similarly, the change of delay times only appears to have very limited effects on the overall environmental impacts of the Erzberg process chain, given the limited contribution to these impacts from the electricity consumed by the primary crushing step. However, in this study, the change of detonation systems was only implemented in the Erzberg mine site. This mining solution is yet to be tested in other energy-intensive mining contexts, where electricity consumption stands out as an environmental hotspot (e.g. as in the Lujar case), before concluding about any potential environmental benefits or burden-shifts. Beyond the life cycle environmental impacts, other benefits may also be expected from controlling delay times, such as reductions in terms of vibrations to the surrounding environment which could, for example, foster the exploitation of mineral deposits located in the vicinity of populated areas.

This study was carried out primarily by use of site-specific data representative of the actual on-site operations in both mines (the data used in this study are partly made available). However, despite the willingness of the mining companies to provide accurate data, some gaps remained and were filled with data from other sources (e.g. literature, LCA databases, etc.). Some aspects indeed remain relatively challenging to account for, in particular regarding emissions to the environment, which may accordingly affect the LCA results. For instance, measuring nitrates emissions from explosives to groundwater is a procedure not always undertaken in mining monitoring, which could ultimately result in under- or overestimations of life cycle environmental impacts, as nitrates emissions to groundwater may have significant impacts in terms of marine eutrophication. Furthermore, emissions of detonation fumes (e.g. CO, NOx, etc.) in the blasting step may be relatively dependent on the measurement procedure implemented, as different methods may yield significantly distinct results.

Other challenges still remain in order to better secure the use of LCA in the mining industry, in particular in terms of impact assessment. Indeed, some of the existing LCA characterization methods are currently subject to debates in the LCA community and may not accurately depict the impacts associated with mining operations, e.g. regarding mineral resource depletion. Moreover, the current methods fail to capture some potential environmental impacts relative to mining operations, and in particular to the blasting step, such as ground vibrations and noise, which may represent important nuisances to the surrounding environment and at the same time significant rooms for improvements thanks to mining solutions as those assessed in this study.

CRediT authorship contribution statement

Frédéric Lai: Conceptualization, Investigation, Writing – original draft, Writing – review & editing. **Antoine Beylot:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing. **Rafael Navarro:** Resources, Writing – review & editing. **Peter Schimek:** Resources, Writing – review & editing. **Philipp Hartlieb:** Resources, Writing – review & editing. **Daniel Johansson:** Resources, Writing – review & editing. **Pablo Segarra:** Resources, Writing – review & editing. **Celso Amor:** Resources, Writing – review & editing. **Jacques Villeneuve:** Conceptualization, Writing – original draft, Writing – review & editing, Supervision.

Declaration of competing interest

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

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Appendix A. Supplementary data

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