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

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1 **Abstract**

2

3 Mining represents the first step to the access to mineral resources. The impacts induced by such
4 operations now contribute to the impacts of a wide range of goods and services, given the
5 widespread use of these raw materials in the worldwide economy. In this context, this study aims at
6 assessing the environmental performance of mining operations in a life cycle perspective,
7 considering two currently operating mine sites: the Erzberg iron open-pit mine (Austria) and the Lujar
8 fluor spar underground mine (Spain). In particular, this study aims at i) identifying the main
9 environmental hotspots along the cradle-to-gate exploitation of mineral deposits in these two mines
10 (“reference scenarios”), ii) assessing the environmental performance of two alternative mining
11 solutions (“alternative scenarios”), respectively the use of alternative explosive compositions
12 (including their associated air emissions) and the implementation of a new blast design method. This
13 assessment relies on representative sets of data primarily drawn from on-site operations and
14 experimental results, completed with other data sources to fill the gaps. The environmental impacts
15 are characterized based on the European EF (Environmental Footprint) life cycle impact assessment
16 method. Firstly, among the 16 impact categories considered, the production of 1 ton of iron
17 concentrate (33.5% Fe) in the Erzberg mine in particular potentially induces a total of 8.75 kg CO₂-eq.
18 The consumption of ferrosilicon in the concentration step (main contributor to 8 impact categories
19 out of 16), of steel in the comminution step (main contributor to 2 impact categories), and of diesel
20 by the machinery necessary for loading/hauling the ore (main contributor to 3 impact categories)
21 stand for the main environmental hotspots in the Erzberg case. Secondly, the production of 1 ton of
22 fluor spar concentrate (79.2% CaF₂) in the Lujar mine potentially induces a total of 174 kg CO₂-eq. The
23 consumption of diesel by the machinery and the on-site generators in the mining and loading/hauling
24 steps (main contributor to 11 impact categories out of 16), along with the mine
25 infrastructure/equipment (main contributor to 4 impact categories) are identified as the main
26 environmental hotspots in the Lujar case. The implementation of both alternative mining solutions
27 results in relatively limited environmental effects on the overall life cycle environmental performance
28 of the Erzberg mining operations (less than 3% difference in terms of impacts). Finally, this study
29 highlights that some challenges still remain to be addressed in order to better secure the use of life
30 cycle assessment in the mining context, in particular in terms of data monitoring/measurement or
31 impact assessment methods.

32

33

34 **Keywords**

35

36 Life cycle assessment; Mining; Environmental impacts; Iron; Fluorspar

37 **Abbreviations and nomenclature**

38

ANFO	Ammonium Nitrate Fuel Oil
CaF₂	Fluorspar
CO	Carbon monoxide
CO₂	Carbon dioxide
E682	Reference of a pure emulsion-based explosive
Fe	Iron
FeSi	Ferrosilicon
GWP	Global Warming Potential
LCA	Life Cycle Assessment
NH₃	Ammonia
NOx	Nitrogen oxides
SOx	Sulfur oxides

39

40

41 1. Introduction

42

43 In 2008, the Raw Materials Initiative set out a strategy for a more reliable and secure access to raw
44 materials in Europe, crucial to the competitiveness and growth of the European Union (EU) economy
45 (EC, 2008). The access to resources is considered a strategic security question by the European
46 Commission (EC), which requires ensuring the supply of sustainable raw materials (EC, 2019). In
47 particular, mineral resources and metals are now key components of many final or intermediate
48 products used in society. Mining and mineral processing are the cradle of their production, the
49 impacts of these activities accordingly contribute to the impacts of many products. More generally,
50 raw materials both hinder and contribute to the 17 Sustainable Development Goals established by
51 the UN 2030 Agenda (Mancini et al., 2019).

52 The environmental impacts of mining and mineral processing may be considered with different
53 views. One of these views is the “mining project” view, under which the impacts are generally
54 considered in light of risk mitigation actions according to territorial legislations in force. Basically, a
55 mining project is submitted to a regulatory-driven impact assessment (IA) covering many aspects of
56 potential pollution releases across the entire process chain, i.e. from the ore extraction to its
57 concentration. Among the main impacts to manage on a mine site, those related to mining (in
58 particular blasting) operations include: ground vibrations (Folchi, 2003; Kuzu and Ergin, 2005;
59 Bhandari, 2016; Jahed Armaghani et al., 2015), air blast overpressure (Kuzu and Ergin, 2005;
60 Bhandari, 2016; Jahed Armaghani et al., 2015), dust (Folchi, 2003; Bhandari, 2016), fly rocks (Folchi,
61 2003; Bhandari, 2016; Jahed Armaghani et al., 2015), noise (Folchi, 2003; Monjezi et al., 2009;
62 Saviour, 2012), nitrates leaching into water or soil (Forsyth et al., 1995).

63 On another note, for more than 20 years, life cycle assessment (LCA) has continuously gained interest
64 for comparing potential environmental impacts of products and services, to the point that its use has
65 become widespread as a support to both policy and company decision-making. LCA has been
66 integrated into several EU environmental policies over the last two decades, e.g. to help define
67 emerging problems (especially related to products and their supply chains, and new technologies)
68 and to help identify policy options (Sala et al., 2016; Sonnemann et al., 2018). By definition, LCA
69 enables undertaking a life cycle perspective, accordingly enlarging the scope of the IA by including
70 upstream and downstream impacts associated with metals production. In particular, given sufficient
71 data, it can enable assessing the contributions of each operation of production to the whole cradle-
72 to-gate impacts of a concentrate or metal production. It enables accounting for both the impacts
73 directly generated by the mine and indirectly generated along the supply-chains the mine is
74 interlinked with. LCA accordingly enables identifying any potential burden-shifting (from one impact
75 category to the other, or from one life-cycle phase to the other) in the comparison of different

76 scenarios. However, it may be noted that, while the IA in the mining project view is spatially and
77 temporally explicit, the life cycle approach generally aggregates emissions across space and time. For
78 example, such a distinction may be relevant regarding dust and pollutants emissions, which are
79 aggregated in space and time in LCA, thus resulting in impacts not representative of actual health
80 risks.

81 The implementation of LCA highlights that mining and concentration stages may have relatively large
82 contributions to the cradle-to-gate environmental impacts of metals production (Nuss and Eckelman,
83 2014), depending on the metal and the impact categories considered. For example, the production of
84 iron (Fe) ore generates relatively low environmental impacts on a per kilogram basis among the 63
85 metals considered by Nuss and Eckelman; however, in the meantime, iron is among the most
86 impactful metals due to its significant global production volume. Among the main environmental
87 hotspots of the iron mining industry, Ferreira and Leite (2015) identify the consumption of electricity
88 as well as grinding media in the iron ore treatment stage as two of the main contributors to the
89 global warming potential (GWP) impacts of iron concentrate production in Brazil; while Norgate and
90 Haque (2010) identify the loading/hauling and crushing/blending steps as the main sources of GWP
91 impacts in the case of iron mining in Australia. Despite these examples of LCA application in the
92 mining industry, assessing the environmental impacts of this sector remains relatively challenging, in
93 particular due to a certain lack of interactions between LCA practitioners and the mining industry
94 (Awuah-Offei and Adekpedjou, 2011). This, in turn, may be partly attributed to the hitherto weak
95 business case for mining companies to undertake LCAs or generate data suitable for input into LCA
96 (Alvarenga et al., 2019).

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

106

107 **2. Material and method**

108 2.1. Case studies description

109 2.1.1. Erzberg mine

110

111 Erzberg is an open-pit iron ore mine located in Eisenerz (Austria). It is considered as the biggest
112 deposit of siderite (FeCO_3) in the world, the iron content within this mineral amounting to about
113 40%. Other iron minerals found in this deposit are primarily ankerites ($\text{Ca}(\text{Fe},\text{Mg},\text{Mn})(\text{CO}_3)_2$), with an
114 iron content varying from 10 to 17%. Currently, the mine annually blasts 12 million tons of ore and
115 waste rock to produce 3 million tons of concentrate (also referred to as fine ore) as final product.
116 Depending on the iron content within the material, different ore fractions are considered:

- 117 • < 22% Fe: cut-off grade below which the material is considered as waste;
- 118 • 22 – 30% Fe: low quality ore also called “middlings”;
- 119 • > 30% Fe: high quality ore (in the following referred to as “rich fraction”).

120 The waste rock, with an iron content below 22%, is discharged to a waste dump; while the ore is
121 loaded and hauled to a primary gyratory crusher (see Figure 1). Depending on its iron content, the
122 crushed ore is separated into middlings and rich fraction. These two ore fractions are then sent to
123 the beneficiation plant in which they go through two different processing routes: on the one hand,
124 middlings are processed through dense media separation, magnetic separation, optical sorting and
125 finally screening/secondary crushing; on the other hand, the rich fraction is only processed through
126 screening/secondary crushing. This results in a concentrate with an average iron content of 33.5%.
127 The beneficiation stage also generates tailings which are either disposed of to a waste dump (coarse
128 tailings) or in dams (fine tailings).

129

130

131

132

Figure 1

133

134 2.1.2. Lujar mine

135

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

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

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

156
157

158 *Figure 2*
159

160

161 2.1.3. Alternative mining solutions and associated scenarios

162

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

- 172 • The first scenario aims at comparing different explosive compositions. In this respect, three
173 alternative compositions are considered in this scenario: i) a pure emulsion (referred to as E682),
174 ii) a blended emulsion composed of E682 and 30% ANFO (Ammonium Nitrate Fuel Oil), and iii) a
175 blended emulsion composed of E682 and 5% aluminum. Tests on these compositions were
176 carried out at laboratory scale, through blasting trials in chambers, with the aim of measuring air

177 emissions resulting from the blasting of the explosives. For comparison purposes, each explosive
178 composition is assumed to be applied in the Erzberg mine, where blasting operations currently
179 use ANFO as well as pure emulsions.

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

194

195 2.2. Goal and scope definition

196

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

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

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

208 Two functional units (FU) are distinguished, as a function of each site under study; respectively, “the
209 production of one ton of iron concentrate, with a Fe-content of 33.5%”, and “the production of one
210 ton of fluorspar concentrate, with an average CaF₂ content of 79.2%”. These FU, with different
211 degrees of purity for each concentrate, imply different levels of efforts (e.g. in terms of electricity

212 consumption) in the ore processing stages (e.g. concentration) but also subsequently in the
213 downstream refining stages (out of the scope of this cradle-to-gate study, which focuses on the
214 mining processes).

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

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

226

227 2.3. Data inventories associated to the scenarios

228

229 The foreground system stands for all the processes for which specific data have been obtained and
230 used in the modelling. The background system, i.e. all the processes upstream and downstream the
231 process chains under study, e.g. electricity generation or ancillary materials production, is modelled
232 by use of data drawn from the ecoinvent v3.5 database (Weidema et al., 2013; Ecoinvent centre,
233 2019).

234

235 2.3.1. Data relative to the Erzberg reference scenario

236

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

243 The primary data encompass:

- 244 • Electricity consumption

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

247 • Diesel consumption

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

249 • Ancillary materials

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

260 • Water balance

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

264 • Emissions to water

265 Include the chemical substances (e.g. chloride, nitrate, sulfate, etc.) as well as the metallic elements
266 (e.g. aluminium, copper, etc.) in the water discharged to the lake in compliance with the local
267 regulations. This water composition is based on laboratory analysis of the water carried out by VA
268 Erzberg GmbH. Moreover, nitrates are also considered to be emitted to groundwater, as these
269 compounds are leached from the explosives used for blasting. Given that no on-site measurements
270 of nitrates leaching were available, a 1% value of the nitrogen contained in the explosives was
271 assumed to be leached to groundwater as nitrates in this study, based on an expert judgement from
272 the explosive manufacturer, supported by estimates drawn from literature (estimates ranging from
273 0.2% (Ferguson and Leask, 1988) up to 28% (Morin and Hutt, 2008) of the nitrogen content within
274 the explosives). Finally, regarding the tailings management in dams, it is assumed in this case that no
275 emissions of metals or other pollutants to water systems occur given the ore mineralogy which is
276 essentially composed of carbonates (i.e. non-sulfidic) and considering that protective measures
277 prevent leaching to the environment. In particular, this assumption is in line with the modelling of
278 non-sulfidic tailings disposal in theecoinvent database, which considers no emissions to the
279 environment.

280 • Emissions to air

281 Include detonation fumes, resulting from blasting (in particular from the explosives), and dust
282 emitted in the mining, crushing and waste disposal steps. The detonation fumes are primarily
283 composed of CO₂, NH₃, CO, SO_x and NO_x, according to calculations from the explosive manufacturer.

284 • Infrastructure and equipment

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

287 • Land occupation

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

290

291 2.3.2. Data relative to the Lujar reference scenario

292

293 The data relative to the “Lujar reference scenario”, which includes all the unit operations from the
294 mining of the fluorspar ore to the final production of a concentrate with an average fluorspar content
295 of 79.2% (see Figure 2), are essentially primary on-site data provided by the Minera de Orgiva, S.L.
296 company. These data are completed with data from other sources in the case of data gaps. The data
297 encompass (see Table 1 for an overview of the data inventory and Supporting Information document
298 2 for the full inventory):

299 • Diesel and electricity consumption

300 Diesel is used to fuel the machinery necessary for drilling and loading/hauling the extracted ore as
301 well as for producing all the electricity necessary to power the mine site through on-site diesel
302 generators. In particular, electricity is consumed to power the plant and the equipment used in the
303 mining, comminution, beneficiation and drying steps. Regarding this last step, it is noteworthy that
304 the dryers are only used in specific moments (during production peaks or raining periods), as part of
305 the material is either dried with the heat generated by the power generators or naturally dried.

306 • Ancillary materials

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

312 • Water balance

313 Includes all the water inputs from different sources (e.g. precipitations, tank supply truck) in the
314 mining and beneficiation steps, as well as the water evaporation in the drying step. It is to be noted

315 that these values express actual water inputs and outputs, and do not include the internal water
 316 recirculation.

317 • Emissions to air and water

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

327 • Emissions to soil

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

330 • Infrastructure and equipment

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

333 • Land occupation

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

336

337

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

338

339 2.3.3. Data relative to the alternative scenario 1

340

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

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

353

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

Explosives	CO	NOx
	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

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2.3.4. Data relative to the alternative scenario 2

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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.

373 **3. Results and discussion**

374 3.1. Environmental impacts of the reference mining scenarios and contribution analysis

375 3.1.1. Erzberg mine

376

377 In a life cycle perspective, the production of 1 ton of iron concentrate with an iron content of 33.5%
 378 at Erzberg potentially induces a total of 8.75 kg CO₂-eq (climate change) and 0.0191 kg N-eq
 379 (eutrophication marine). The complete list of impacts, considering the 16 categories of the EF
 380 method 2.0, is provided in Table 3.

381

382 *Table 3: Environmental impacts induced by the production of 1 ton of iron concentrate (33.5% Fe) at Erzberg, considering 16*
 383 *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

384

385 Overall, the concentration step stands out as the main contributor to most of the impact categories
 386 considered (9 out of 16): climate change, ionizing radiation, photochemical ozone formation,
 387 respiratory inorganics, non-cancer human health effects, acidification terrestrial and freshwater,
 388 eutrophication freshwater, water scarcity and resource use - energy carriers (Figure 3). Regarding
 389 these nine impact categories, the concentration step accounts for 40 to 78% of the impacts.

390 Moreover, it also appears as a major contributor to impacts on ozone depletion, cancer human
391 health effects, eutrophication marine, eutrophication terrestrial, and ecotoxicity freshwater (second
392 contributor, with 30 to 42% of the impacts). The concentration step is overall a hotspot for 14 impact
393 categories out of the 16 under study.

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

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

406 Finally, the mining step significantly contributes to the land use and resource use - mineral and
407 metals impact categories but has limited contributions regarding the other categories (less than
408 10%); while the waste/tailings disposal step solely contributes to the land use impact category.
409 Similarly, the dewatering step is the second contributor to the ionizing radiation impact category but
410 only represents a slight share of the impacts regarding all the other categories (less than 11%).

411

412

413

414

415

Figure 3

416 Over the entire Erzberg process chain, the use of chemicals and ancillary materials stands for the
417 main environmental hotspot as their use induces the largest share of the impacts regarding 10 out of
418 the 16 impact categories considered in this study (39 to 90% of the impacts; Figure 4), encompassing
419 the impact categories respectively dominated by the concentration (8 categories excepting ionizing
420 radiation) and the primary crushing (2 categories) steps. In particular, these impacts are primarily
421 driven by the use of ferrosilicon (FeSi) in the concentration step, except for the toxicity-related
422 impact categories (human health effects and ecotoxicity) for which the impacts are primarily driven
423 by the use of steel as grinding media in the primary crushing step, and to a lower extent, in the
424 concentration step. It is however to be noted that the steel consumption value considered in this

425 case is drawn from the Lujar data, in the absence of specific data relative to the Erzberg situation,
426 which may therefore imply some uncertainties.

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

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

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

446

447

448

Figure 4

449

450

451 3.1.2. Lujar mine

452

453 In a life cycle perspective, the production of 1 ton of fluorspar concentrate with a fluorspar content
454 of 79.2% at Lujar potentially induces a total of 174 kg CO₂-eq (climate change), 0.56 kg N-eq
455 (eutrophication marine). The complete list of impacts, considering the 16 categories of the EF
456 method 2.0, is provided in Table 4.

457

458 *Table 4: Environmental impacts induced by the production of 1 ton of fluorspar concentrate (79.2% CaF₂) at Lujar,*
 459 *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

460
 461 Overall, the mining step stands out as the main environmental hotspot with respect to all impact
 462 categories considered in this study except for the eutrophication freshwater category for which
 463 mining represents the second largest contribution (Figure 5). In particular, the mining step accounts
 464 for 41 to 44% of the impacts with respect to 10 categories: climate change, ozone depletion, ionizing
 465 radiation, photochemical ozone formation, respiratory inorganics, acidification terrestrial and
 466 freshwater, eutrophication marine, eutrophication terrestrial, water scarcity and resource use -
 467 energy carriers. Regarding the other impact categories, it contributes to 21 to 32% of the total
 468 impacts.

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

475 Moreover, the concentration step accounts for 9 to 32% of the impacts regarding all categories, with
476 more significant contributions in terms of non-cancer human health effects, eutrophication
477 freshwater, land use and water scarcity (more than 20% of the total impacts). Similarly, the
478 comminution step also accounts for 9 to 26% of the impacts regarding all categories excepting the
479 respiratory inorganics category, with more important contributions to the non-cancer and cancer
480 human health effects and resource use - mineral and metals impact categories.

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

484

485

486

Figure 5

487

488

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

501 Regarding the mine infrastructure/equipment, the latter represents the largest share of the impacts
502 in terms of non-cancer human health effects, eutrophication freshwater, land use and resource use -
503 mineral and metals. It is however to be noted that, as mentioned in the data inventory section
504 (2.3.2), the modelling of this infrastructure/equipment relies on data drawn from ecoinvent v3.5,
505 which may not be totally representative of the actual infrastructure/equipment of the Lujar mine.
506 Moreover, while the mining operator may control its on-site diesel consumption and accordingly its
507 associated impacts, the impacts associated with the infrastructure and equipment are rather
508 generated upstream along supply chains (e.g. in the production of materials composing the
509 equipment), where the mining operator hardly has any influence.

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

518

519

520

Figure 6

521

522

523 3.2. Scenarios comparison: reference vs alternative scenarios

524 3.2.1. Change of explosives composition and associated emissions

525

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

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

540 In three cases of impact categories (eutrophication terrestrial, acidification terrestrial and
541 freshwater, and photochemical ozone formation), the larger impact is mainly driven by the larger
542 emission factors considered for CO and NO_x from blasting. For example, the larger emission factor
543 associated with NO_x induces approximately 90% of the increase in impacts with respect to

544 eutrophication terrestrial. On the contrary, regarding most other impact categories, the larger
545 impacts of the alternative explosives are essentially driven by their more impacting manufacture.

546

547

548

Figure 7

549

550

551 3.2.2. New blast design method implementation

552

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

556 When exclusively focusing on the primary crushing step, the change of delays only marginally affects
557 the impacts (less than 0.5% reduction in impacts) regarding five impact categories: respiratory
558 inorganics, non-cancer and cancer human health effects, ecotoxicity freshwater and resource use -
559 mineral and metals. As for the other impact categories considered in this study (Figure 8), the
560 decrease in impacts varies from 2% (photochemical ozone formation) up to 8% (resource use –
561 energy carriers) with respect to the reference Erzberg scenario, excepting in terms of ionizing
562 radiation and land use, for which the reduction in impacts appears to be larger, respectively reaching
563 20% and 14% (considering delay 1).

564

565

566

Figure 8

567

568

569 3.3. Environmental performance of the Erzberg and Lujar mining operations: sensitivity analysis

570 3.3.1. Sensitivity to nitrates leaching from explosives

571

572 Nitrates leaching from ammonium nitrates-based explosives (e.g. ANFO, emulsion, etc.) is a well-
573 known phenomenon in the mining industry. Such leaching may affect and contaminate surrounding
574 water systems, in particular groundwater. As described in the inventory section relative to Erzberg
575 (2.3.1), 1% of the nitrogen content within the explosives was assumed to be leached to groundwater
576 in the form of nitrates, based on an expert judgement supported by literature data. However, this 1%
577 value may be considered as a conservative value in comparison with the estimates drawn from
578 literature (0.2 up to 28%). Indeed, while emissions of nitrates to groundwater do not appear to

579 significantly contribute to the overall life cycle environmental impacts of the Erzberg process chain
580 when considering a 1% value (Figure 4); when considering the upper bound of nitrates leaching value
581 provided by the literature, i.e. 28%, the impacts over the entire Erzberg process chain show a 77%
582 increase in terms of eutrophication marine (while other impact categories are not affected by a
583 change of nitrates emissions value given the absence of characterization factors associated to
584 nitrates emissions to groundwater). In that case, such a discrepancy highlights that the
585 environmental performance of mining operations may be very sensitive to the amount of nitrates
586 emitted to groundwater from the explosives, and emphasizes the need for accurate on-site
587 measurements of these leakages.

588

589 3.3.2. Sensitivity to electricity supply

590

591 While electricity does not significantly contribute to the environmental impacts in the Erzberg case, it
592 stands for an environmental hotspot in the Lujar case. Figure 9 compares the environmental impacts
593 of the Lujar mining operations as functions of different sources of electricity supply, namely
594 electricity from the Spanish grid mix and electricity from the grid entirely supplied from renewable
595 sources (on the one hand, photovoltaic power station and on the other hand, wind turbine), with the
596 reference scenario. Data regarding the electricity production from these different sources are drawn
597 from the ecoinvent v3.5 database. Depending on the sources of electricity supply, important
598 discrepancies can be observed in terms of life cycle environmental impacts. Indeed, on the one hand,
599 the consumption of electricity from the Spanish mix increases the impacts with respect to 11
600 categories out of 16, primarily driven by the share of fossil (hard coal and oil in a lower extent) and
601 nuclear sources in the mix: climate change (+ 2%), ionizing radiation (+ 407%), non-cancer and cancer
602 human health effects (respectively + 51% and + 8%), acidification terrestrial and freshwater (+ 20%),
603 eutrophication freshwater (+ 79%), ecotoxicity freshwater (+ 20%), land use (+ 49%), water scarcity (+
604 186%) and resource use – energy carriers and mineral/metals use (respectively + 27% and + 4%).
605 Regarding the five remaining impact categories, the Spanish mix leads to a decrease in impacts
606 ranging from 13% to 25%. On the other hand, the consumption of electricity from renewable sources
607 overall enables a reduction in impacts regarding most impact categories considered (respectively 12
608 and 14 categories for the photovoltaic power station and the wind turbine scenarios, with 4 up to
609 49% of reduction in impacts), except for a few categories: cancer human health effects (+ 0.2%
610 impacts for wind turbine), eutrophication freshwater, ecotoxicity freshwater, land use (1 to 28%
611 increase in impacts for the photovoltaic power station) and resource use – mineral and metals (8 –
612 9% increase in impacts for both renewable sources). These results highlight that the environmental
613 performance of mining operations may be very sensitive to the source of electricity supply, and that

614 renewable energies overall appear as promising alternatives towards mitigating their associated
615 environmental impacts.

616

617

618

Figure 9

619

620

621 3.4. Positioning of this study with respect to the state-of-the-art

622

3.4.1. Positioning with respect toecoinvent

623

624 In comparison with the data relative to iron (Classen et al., 2009) and fluorspar (Jungbluth et al.,
625 2009) concentrates production available in the widely used ecoinvent database (in its 3.5 version),
626 the two mining case studies considered in this study offer relatively different insights. Firstly, the
627 products considered in ecoinvent differ from those of the Erzberg and Lujar mines in terms of purity,
628 as ecoinvent respectively considers an iron concentrate with a 65% Fe content (33.5% Fe in the
629 Erzberg concentrate) and a fluorspar concentrate with a 97% CaF₂ content (79.2% CaF₂ in the Lujar
630 concentrate). These different degrees of purity in the concentrates therefore imply different
631 functional units between the ecoinvent database and this study. Moreover, the ore grades
632 considered in ecoinvent also differ from those of this study: 46% Fe in the ecoinvent iron ore (from
633 22% up to more than 30% Fe in Erzberg) and 92% CaF₂ in the ecoinvent fluorspar ore (45.5% CaF₂ in
634 Lujar). Consequently, these different grades and purities imply different processing requirements,
635 which translate in the data inventories, e.g. in terms of electricity, diesel, heat consumptions or
636 emissions to the environment. It may be noted that these discrepancies in terms of purity imply
637 different requirements, on the one hand, in the ore processing stages (e.g. concentration) in which a
638 higher purity in the concentrate may require more processing efforts, on the other hand, in the
639 downstream refining stages in which a higher purity in the concentrate may require less processing
640 efforts. Therefore, one possibility for ensuring a fair comparison between concentrates with different
641 degrees of purity could be to expand the system boundaries by including the downstream stages
642 until the production of a refined product (which however are out of the scope of this study).

643 Secondly, in the case of fluorspar, significant differences can be observed between the process
644 chains considered in ecoinvent and the Lujar mine (while for iron the process chains are relatively
645 similar). Indeed, the Lujar mine exploits fluorspar through underground mining operations
646 subsequently followed by gravity concentration, whereas ecoinvent only considers open-pit mining
647 operations subsequently followed by flotation.

648 These important differences in the modelling of iron and fluorspar concentrates production result in
 649 significant discrepancies in terms of impacts assessment results, with differentials amounting to
 650 several orders of magnitude betweenecoinvent and this study (respectively 3 to 35 and 0.5 to 6
 651 orders of magnitude for iron and fluorspar productions; Figure 10).

654 *Figure 10*

656
 657 3.4.2. Positioning with respect to scientific literature

658
 659 The number of LCA studies specifically addressing the environmental impacts of iron and fluorspar
 660 mining overall appears relatively limited in the scientific literature. No studies were found to address
 661 fluorspar mining, while regarding iron ore mining only two studies were found (Table 5): on the one
 662 hand, Ferreira and Leite (2015) focused on the exploitation of iron ore (with an average Fe content of
 663 43%) in an open-pit mine in Brazil, producing an iron concentrate as final product; on the other hand,
 664 Norgate and Haque (2010) considered the production of an iron ore (with an average Fe content of
 665 60%) in an open-pit mine in Australia.

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

677
 678 *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	> 22% Fe (in ore) 33.5% Fe (in concentrate)	8.75

Fe-content of 33.5%"			
(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

679

680

681 3.5. Limitations

682 3.5.1. Limitations relative to the impact assessment in this study

683

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

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

699 Finally, results regarding some impact categories should be considered with caution, as the
700 underlying characterization models associated to several categories may show some limits e.g.
701 regarding resource depletion or toxicity to humans and ecosystems (Santero and Hendry, 2016). For
702 example, the impacts associated with resource use – mineral and metals are calculated based on the
703 abiotic depletion potential (ADP) approach, which considers the depletion of a resource once it is
704 extracted from the Earth’s crust by accounting for the reduction of its geological stock. Accordingly,
705 such an approach attributes most of the impacts in terms of resource depletion to the mining step,
706 as it is responsible for the extraction of the resource (as e.g. observed in the Erzberg reference

707 scenario). However, such a perspective may be seen rather limited, as the resource is not necessarily
708 depleted right after its extraction, but rather remains in an “anthropogenic stock” (Berger et al.,
709 2020). In this context, approaches are currently under development to account for resource
710 dissipation in LCA, focusing on the actual losses of resources along process and more generally life-
711 cycle chains, rather than resource extraction, in order to support more resource-efficient solutions
712 (Beylot et al., 2020a; Beylot et al., 2020b). On another note, while most environmental impacts may
713 be considered permanent, impacts in terms of land use may rather be considered temporary, as they
714 reflect the use and occupation of the land over the period of activity of the mine. Once the activity
715 ceases, these land use impacts may potentially be mitigated through mine closure practices (e.g.
716 restoration, reclamation or rehabilitation; Limpitlaw and Briel, 2014).

717

718 3.5.2. Limitations relative to the impact assessment in the overall mining context

719

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

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

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

739

740 4. Conclusions

741

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

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

769 This study was carried out primarily by use of site-specific data representative of the actual on-site
770 operations in both mines (the data used in this study are partly made available). However, despite
771 the willingness of the mining companies to provide accurate data, some gaps remained and were
772 filled with data from other sources (e.g. literature, LCA databases, etc.). Some aspects indeed remain
773 relatively challenging to account for, in particular regarding emissions to the environment, which
774 may accordingly affect the LCA results. For instance, measuring nitrates emissions from explosives to

775 groundwater is a procedure not always undertaken in mining monitoring, which could ultimately
776 result in under- or overestimations of life cycle environmental impacts, as nitrates emissions to
777 groundwater may have significant impacts in terms of marine eutrophication. Furthermore,
778 emissions of detonation fumes (e.g. CO, NO_x, etc.) in the blasting step may be relatively dependent
779 on the measurement procedure implemented, as different methods may yield significantly distinct
780 results.

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

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790

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943 **Figures**

944

945 Figure 1: Flowsheet of the Erzberg process

946

947 Figure 2: Flowsheet of the Lujar process

948

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

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952 Figure 4: Environmental impacts of iron concentrate production at Erzberg – contributions by types
953 of exchanges with technosphere/environment, considering 16 impact categories from the EF method
954 2.0

955

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

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

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

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967 Figure 8: Environmental impacts of the primary crushing operation at Erzberg, as functions of
968 different delay times set in the blasting step and compared with the reference scenario (set to
969 100%), considering 11 impact categories from the EF method 2.0

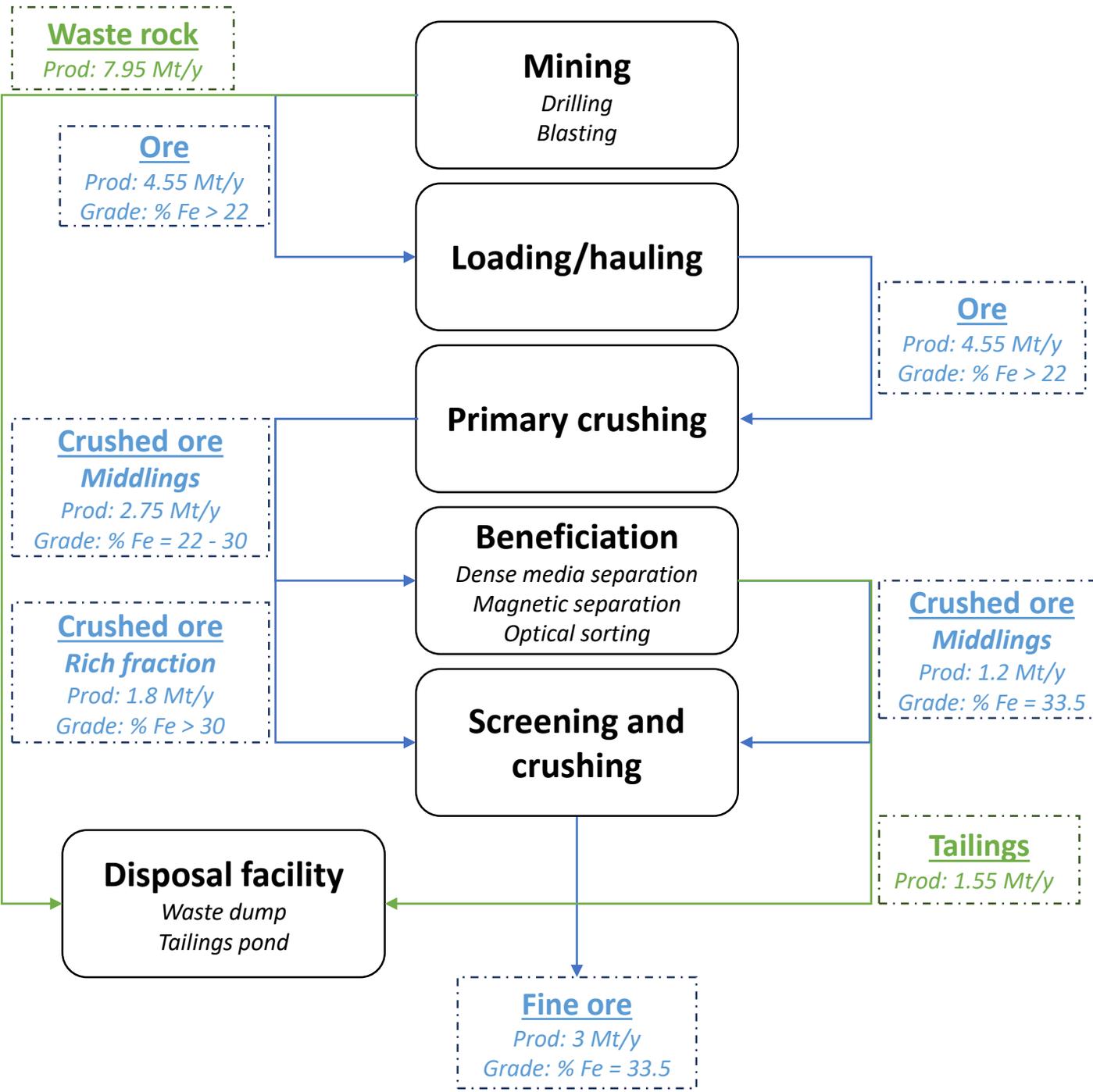
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971 Figure 9: Environmental impacts of the Lujar mining operations, as functions of different sources of
972 electricity supply compared with the reference scenario (set to 100%), considering 16 impact
973 categories from the EF method 2.0

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975 Figure 10: Environmental impacts of iron and fluorspar concentrates production from the ecoinvent
976 v3.5 database, respectively compared to the Erzberg and Lujar reference scenarios (set to 100%),

977 considering 1 ton of concentrate (with different degrees of purity) and 16 impact categories from the
978 EF method 2.0 (Ei = ecoinvent)



Waste rock

Prod: 2.68 t/h

Grade: % $\text{CaF}_2 = 3.26$

Ore

Prod: 4.92 t/h

Grade: % $\text{CaF}_2 = 45.5$

Ground ore

Prod: 4.92 t/h

Grade: % $\text{CaF}_2 = 45.5$

Mining

Hydraulic breaking
Drilling
Blasting

Loading/hauling

Trucks
Articulated haul trucks
Low profile loaders

Comminution

Jaw crushing
Vibratory screening
Hopper storage

Beneficiation

Dense media separation
Vibratory screening
Gravity concentration

Drying

Backfill

Ore

Prod: 4.92 t/h

Grade: % $\text{CaF}_2 = 45.5$

Concentrate

Prod: 2.03 t/h

Grade: % $\text{CaF}_2 = 79.2$

Tailings

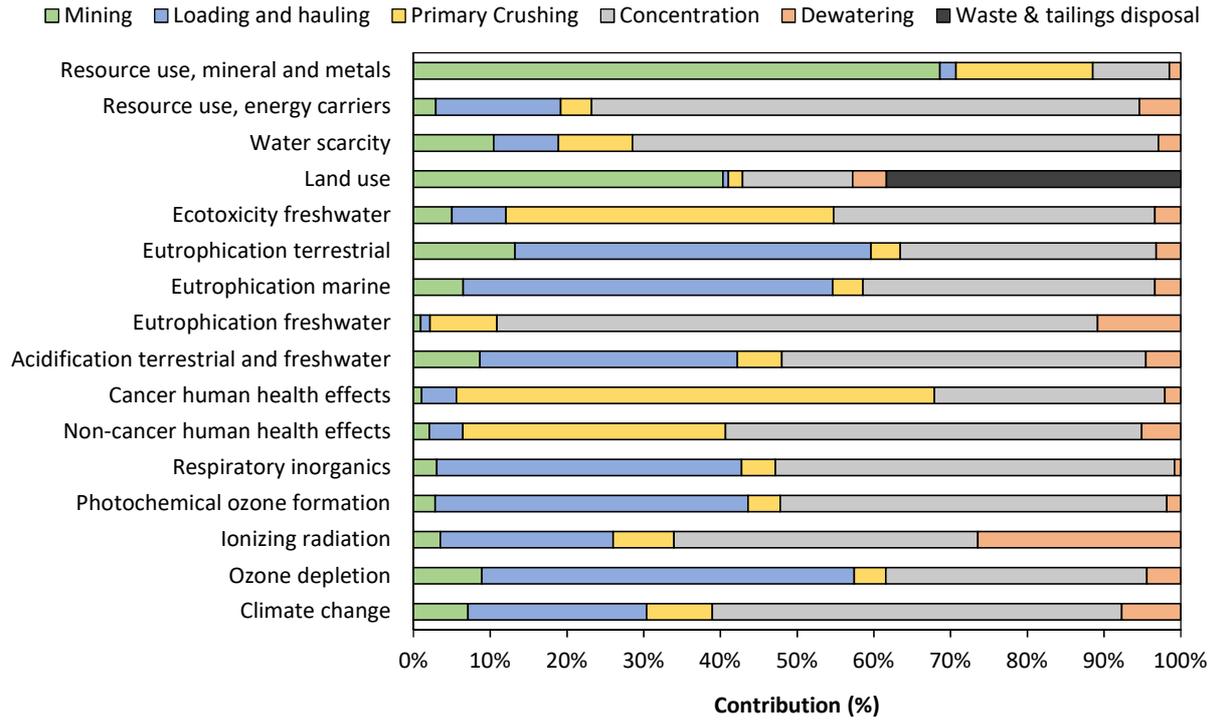
Prod: 2.89 t/h

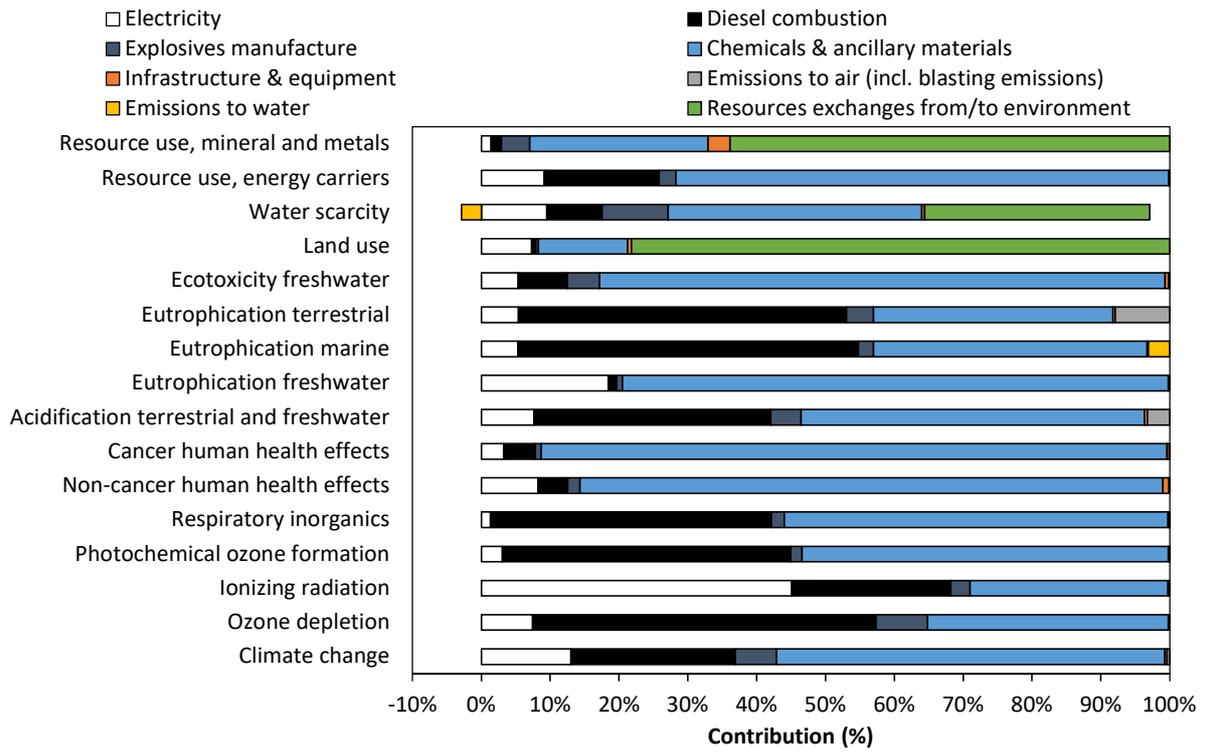
Grade: % $\text{CaF}_2 = 24.5$

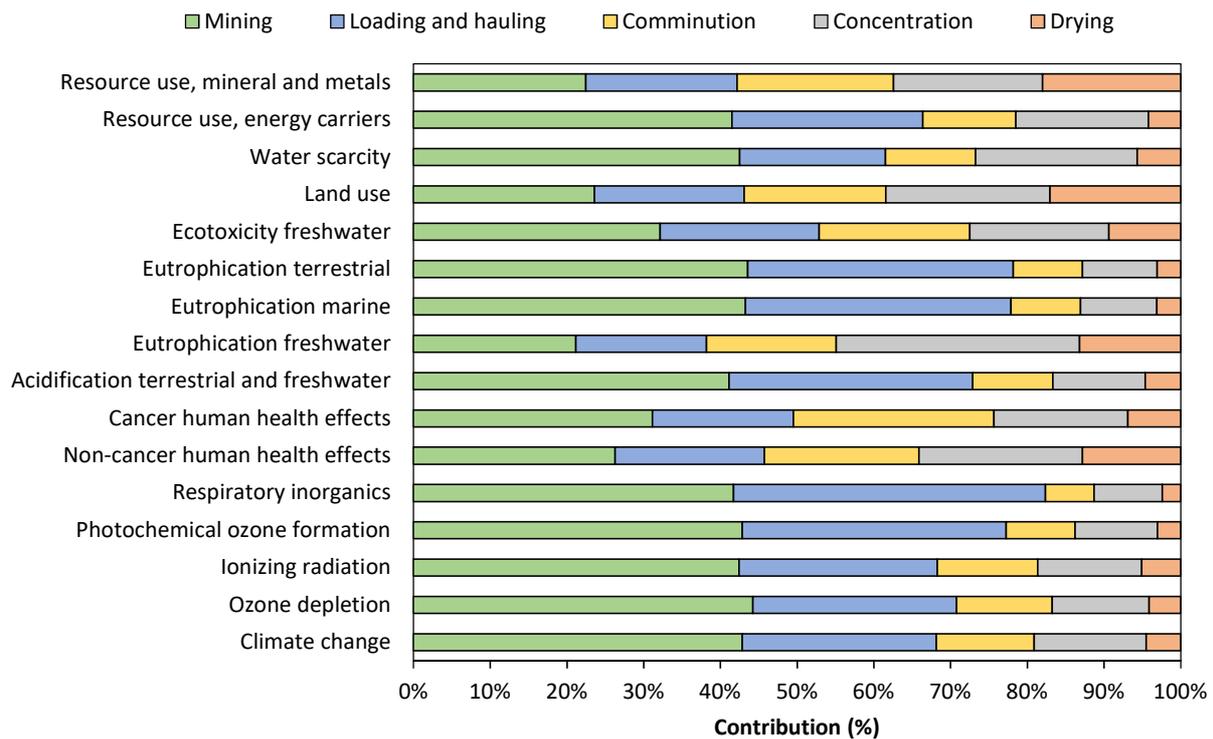
Concentrate

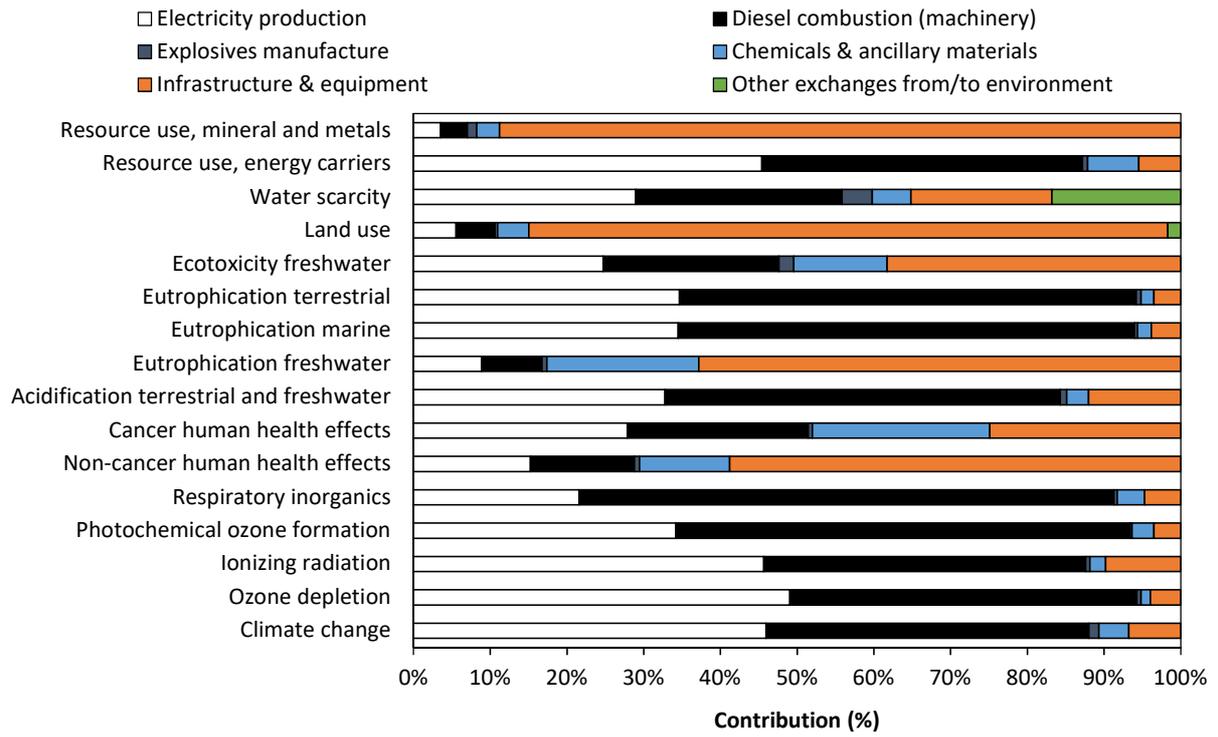
Prod: 2.03 t/h

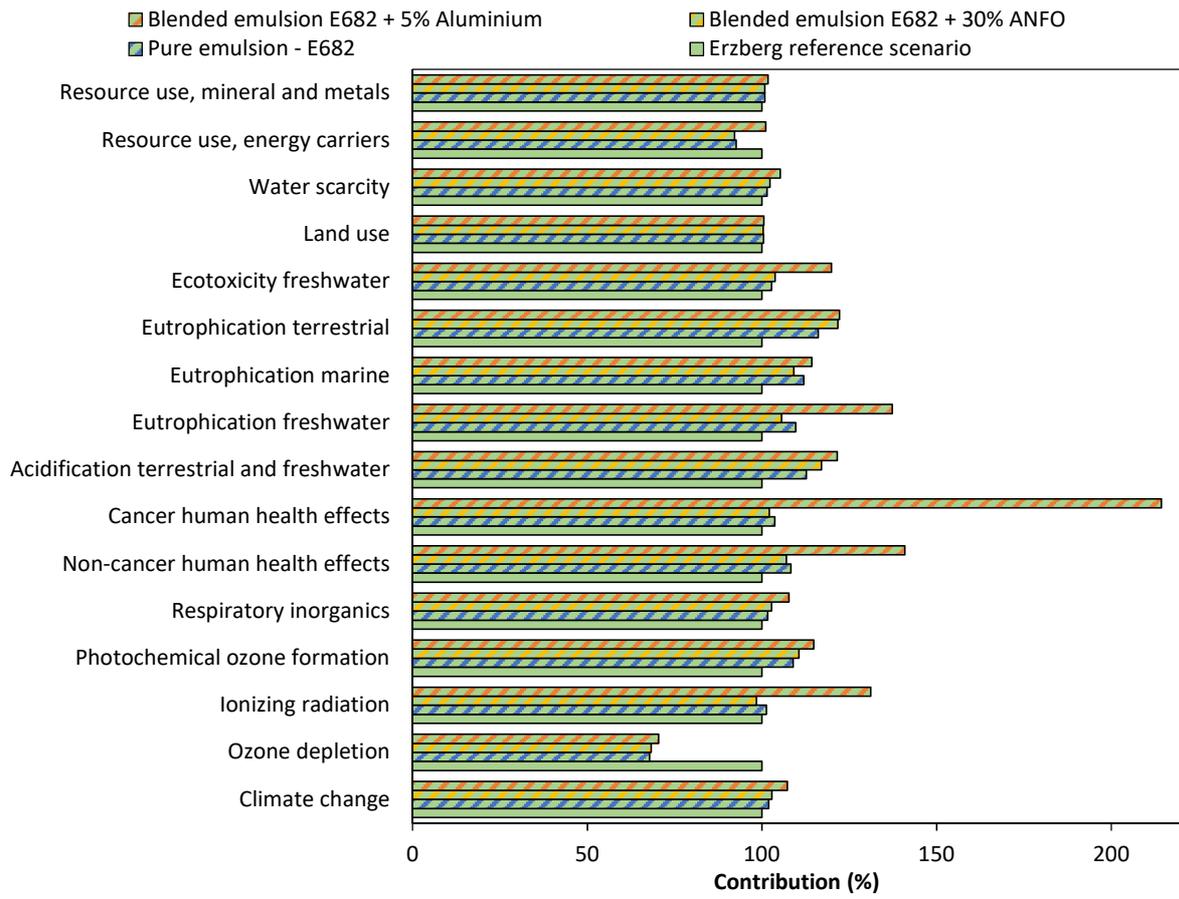
Grade: % $\text{CaF}_2 = 79.2$

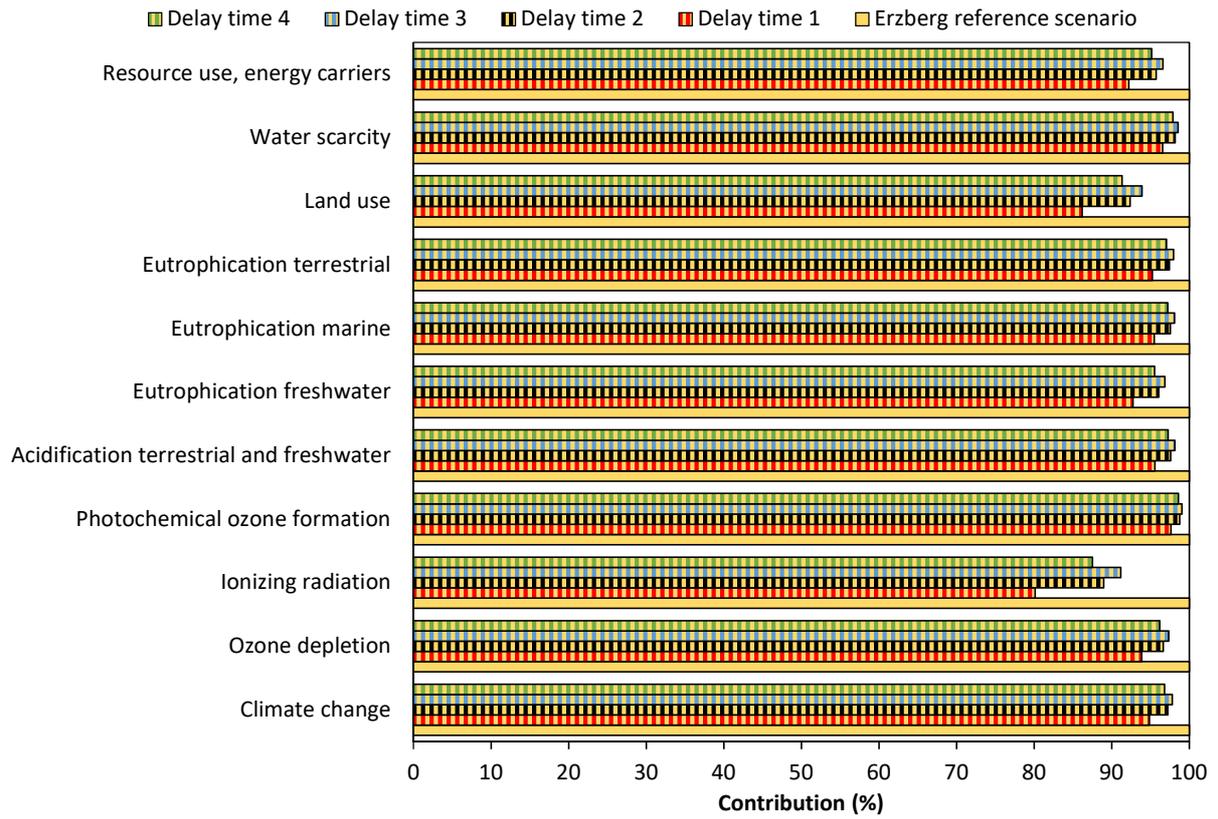


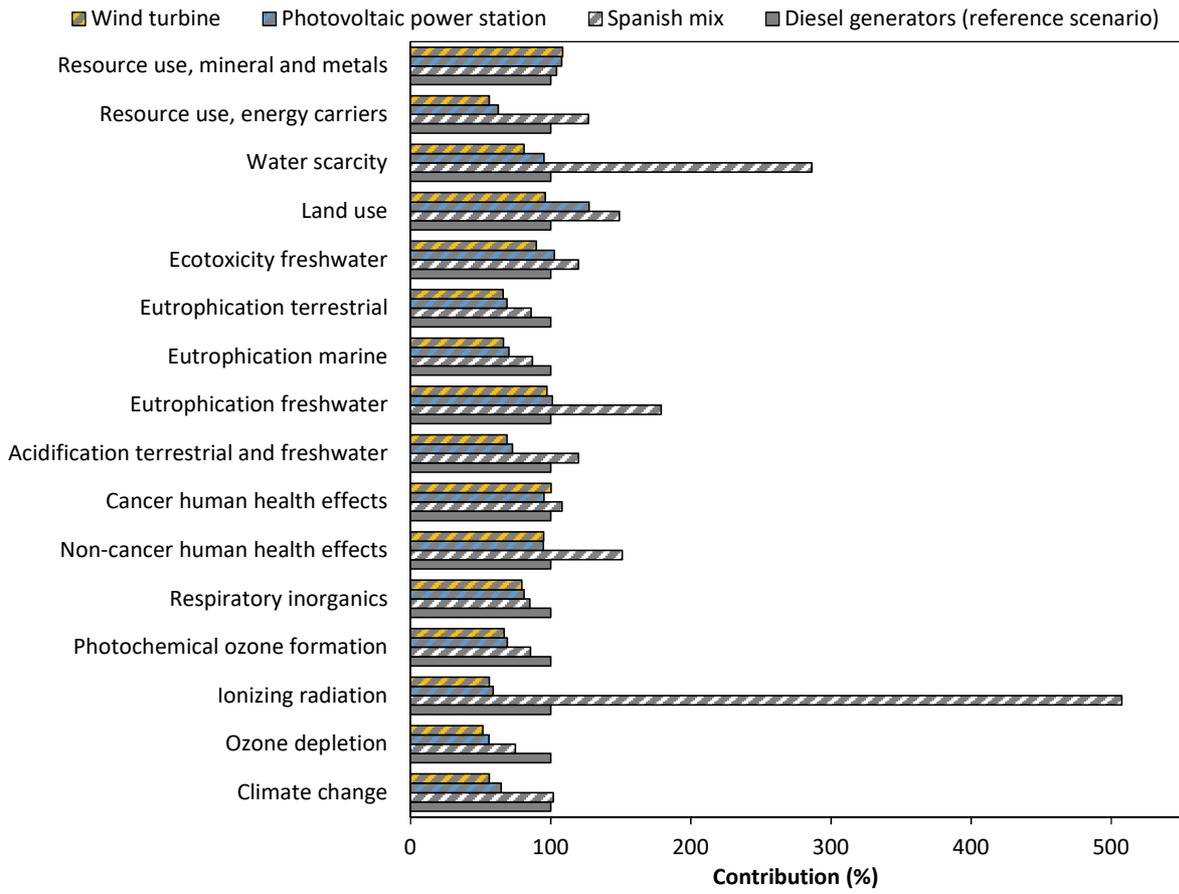


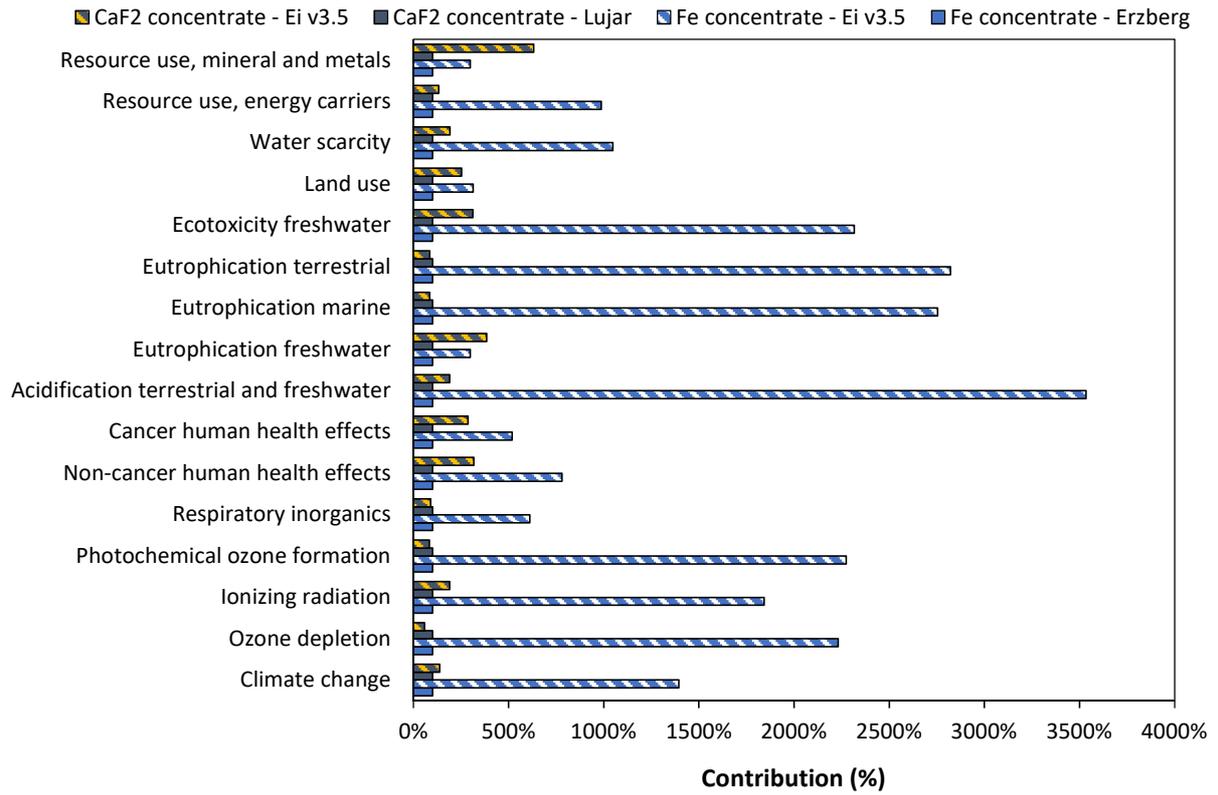












Iron (Fe) mining



Fluorspar (CaF₂) mining



Life cycle assessment (LCA)

- **Contributions analysis: identification of environmental hotspots**
- **Scenarios comparison: alternative mining solutions**
- **Sensitivity analysis: nitrates leaching, electricity mix**

