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Switch on-switch off small-scale mining: environmental performance in a life cycle perspective

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1 **Abstract**

2 A switch on-switch off (SOSO) approach to mining relies on an integrated modular and mobile plant.
3 It is appropriate for rapid start-up and cessation of production from ore deposits that have economic
4 viability dependent on fluctuating commodity prices. This study aims at assessing the environmental
5 performance of the SOSO approach in a life cycle perspective, using evidence collected during its
6 pilot-scale implementation on a high-grade lead deposit located in Bosnia-Herzegovina. The deployed
7 modules include: i) a selective mining tool, ii) a comminution module with crusher and screen, and iii)
8 a gravity separation module with screen, spirals and a shaking table. The Life Cycle Inventory is based
9 on a comprehensive and transparent set of data, drawn from the on-site pilot tests, completed with
10 additional calculations (including process simulation with USIM-PAC®), scenarios (regarding energy),
11 and some generic data and assumptions. The potential environmental impacts are calculated
12 considering 13 impact categories of the EF 2.0 impact assessment method. The production of one
13 tonne of Pb concentrate, with a Pb-content of 58.7%, induces in particular the potential generation
14 of 897 kg CO₂-eq. Moreover, the contribution analysis enables identification of the environmental
15 hotspots, including the consumption of electricity supplied by on-site diesel generators that
16 contributes to more than 90% of the total impacts in seven impact categories. Finally, this article
17 discusses i) how advantageous the SOSO approach is compared to large-scale lead mining regarding
18 some of its associated key environmental hotspots, ii) the potential for reduction of the impacts
19 associated with electricity consumption, in particular through the implementation of a renewable
20 electricity supply mix (solar photovoltaics and biomass-based), iii) the contributions of equipment
21 and tailings to the total impacts, and iv) the contribution of the SOSO approach to resource
22 accessibility and depletion. The inclusion of data outputs of mineral processing simulation in LCA
23 appears a promising development towards optimization of the SOSO modular process chain, based
24 on life-cycle environmental criteria and accounting for the site-dependent variability of ores and
25 processes.

26

27 Key words: LCA, process simulation, lead, small-scale mining, environmental impacts

28 **1. Introduction**

29 In 2008, the European Commission (EC) introduced The Raw Materials Initiative that set out a
30 strategy for a more reliable and secure access to raw materials in Europe, viewed as crucial to the
31 competitiveness and growth of the European Union (EU) economy (EC, 2008). The sustainable supply
32 of raw materials from within the EU was one of the three pillars of this strategy. Moreover, the EC
33 introduced a list of Critical Raw Materials in 2011, which was updated in 2014 and 2017. More
34 recently, in the context of Europe’s ambition to deliver the Green Deal, access to resources has been
35 reaffirmed as a strategic security question by the EC. In particular, there is a requirement to ensure a
36 supply of sustainable raw materials, especially those critical for low-carbon technologies, digital,
37 space and defence applications (EC, 2019).

38 Europe has been actively mined over many centuries. Today, the exploitation of former mine sites
39 and of small deposits, where larger mining operations may not be feasible, appears as one of the
40 major opportunities to access raw materials in the European territory (EC, 2013). Europe has a large
41 number of small and complex mineral deposits, particularly of critical and strategic raw materials as
42 reported in European mineral resources databases such as ProMine or Minerals4EU¹ (Cassard et al.,
43 2014; Cassard et al., 2015). However, so far, their exploitation has been considered not economically
44 viable, due to a short life-of-mine that cannot justify large capital investment in infrastructure, and
45 insufficient returns (Moore et al., 2020). Accordingly, new business and technology solutions are
46 necessary to enable the small-scale mining (SSM) of these deposits, while ensuring low levels of
47 environmental and social adverse effects (Sidorenko et al, 2020). Compared to artisanal mining, SSM
48 in Europe will i) have higher overheads, ii) use advanced extraction and processing technologies, and
49 iii) employ small but trained workforce (Sidorenko et al., 2020). Switch on-switch off (SOSO) is one
50 approach to small-scale mining, which relies on modularised mobile plants, transported between
51 sites and adaptable to the local site-conditions. In this context, the EU-funded project IMP@CT²
52 proposed to develop a new SOSO mining approach to exploit the valuable deposits that are not
53 amenable to large-scale mining operations. The project ended with two on-site pilot test works
54 respectively on the lead mine of Olovo (Bosnia-Herzegovina) and on the Veliki Majdan mine for
55 processing antimony ore from the Zajača deposit (Serbia) (Moore et al., 2020; Moore, 2019; Moore
56 et al., 2018; Bodin et al., 2019). These two deposits are representative of a number of small deposits
57 in Europe: moderately or extensively explored, previously mined, reasonably well-understood, and
58 therefore potentially representing an excellent opportunity for rapid switch-on production in
59 response to short-term changes in market forces.

¹<http://promine.gtk.fi/> and <http://minerals4eu.brgm-rec.fr/>

² <http://www.impactmine.eu/> and <https://cordis.europa.eu/project/id/730411>

60 Raw materials have a twofold role with respect to the 17 Sustainable Development Goals established
61 by the United Nations (UN) 2030 Agenda (UN General Assembly, 2015), both hindering and
62 contributing to their achievement (Mancini et al., 2019). For instance, the production of metals
63 implies the generation of greenhouse gases, but their use in renewable energy technologies may
64 contribute to limit the greenhouse gases induced by the energy production sector. In the last 20
65 years, Life Cycle Assessment (LCA) has been ever more widely implemented to assess the potential
66 environmental impacts of (primary and secondary) metals production in a cradle-to-gate perspective.
67 Published studies considered either a large set of different metal elements (Nuss and Eckelman,
68 2014), or a more limited set of specific metal elements such as those potentially targeted in the
69 future through the implementation of the IMP@CT SOSO mining approach in Europe. These include,
70 for example, lead (Pb; Davidson et al., 2016; Hong et al., 2017), zinc (Zn; Van Genderen et al., 2016;
71 Qi et al., 2017) or gold (Au; Chen et al., 2018), in some cases focusing only on the production of a
72 concentrate (e.g. Pb and Zn concentrates; Tao et al., 2019).

73 LCA studies in particular enable analysts: i) to provide an overall quantification of the potential
74 environmental impacts of metals production, considering large-scale (regional, or even worldwide)
75 data from operating plants (e.g. regarding Pb and Zn; Davidson et al., 2016; Van Genderen et al.,
76 2016); ii) to identify and discuss environmental impact hotspots along the process chains either at a
77 fully operating stage or at a development stage (e.g. regarding Zn, Qi et al., 2017; Pb and Zn
78 concentrates, Tao et al., 2019; Au, Chen et al., 2018); iii) to further analyse the environmental
79 benefits of potential actions on these hotspots (e.g. regarding Pb and manganese; Hong et al., 2017;
80 Zhang et al., 2020); and iv) to support the comparison between several options of processing routes,
81 based on their environmental performance (e.g. regarding Au; Elomaa et al., 2020).

82 The contribution of the mining and concentration stages to the overall environmental impacts of
83 metals production is relatively important (as e.g. observed by Nuss and Eckelman, 2014; Davidson et
84 al., 2016; Qi et al., 2017). This implies that improvement of the environmental performance of these
85 stages would benefit the whole metals production chain, to an extent that depends on the impact
86 categories and the metals concerned. Although LCA has been extensively applied to the minerals
87 industry, mining and processing operations are still often described using generic, averaged values or
88 “black box models”, rendering the identification of environmental hotspots difficult (Segura-Salazar
89 et al., 2019).

90 In this context, this study aims at assessing the environmental performance of the SOSO mining
91 approach in a life cycle perspective, considering its pilot-scale implementation on a high-grade lead
92 deposit located in Bosnia-Herzegovina. Beyond the quantification of the potential environmental

93 impacts of the SOSO mining approach, the objective is twofold: i) identifying the main contributions
94 to impacts (“environmental hotspots”), and ii) accordingly discussing potential areas for
95 improvements and risks of trade-offs in impacts in the future development and widespread use of
96 the SOSO mining approach.

97 **2. Method**

98

99 *2.1 IMP@CT process-chain description*

100 The IMP@CT project has developed an integrated, mobile solution combining selective underground
101 mining with ore sorting and adaptable flowsheet designs for processing different types of ores. In
102 particular, a prototype mining tool for selective mining of narrow veins, steeply dipping high-grade
103 deposits has been specifically developed in the framework of the project. Ore processing
104 technologies are deployed in “modules” of equipment including X-ray fluorescence (XRF)-based ore
105 sorting, ore comminution, and gravity separation. These mineral processing unit operations and their
106 ancillary equipment are containerized so that they can be stored, transported from site to site,
107 rapidly deployed and (re)-commissioned, and readily operated.

108 The IMP@CT SOSO approach can be adapted for its application to a range of small European deposits
109 rich in elements such as lead, antimony, and other (including critical) metals (Moore, 2018). In the
110 framework of the IMP@CT project, it has been specifically deployed at a pilot-scale to the case of a
111 Pb-rich deposit located in Olovo (Bosnia-Herzegovina). The Olovo Pb deposit is hosted by carbonate
112 rocks where cerussite (PbCO₃) is the main mineral (Palinkaš et al. 2008; 2016).

113 In Olovo, the deployed modules of the IMP@CT solution included: i) a selective mining tool to extract
114 a high-grade cerussite ore from mineralized veins (5-6% of lead); ii) a comminution module with
115 crusher and screen in order to reduce the ore into particles smaller than 5 mm; and iii) a
116 classification and gravity separation module with screen, spirals and a shaking table in order to
117 produce a lead concentrate (50-60% of lead; Figure 1). The deployment of these technologies in
118 Olovo took place at various stages from July 2018 to July 2019 and included transportation,
119 installation, the establishment of health and safety procedures, commissioning and test works. It is to
120 be noted that in the case of the Olovo pilot site, the XRF-based ore sorting technology was tested at a
121 pilot scale on sized ore blocks but not integrated into the overall production chain of a cerussite
122 concentrate. In the context of other deposits and depending on their ore characteristics,
123 development and deployment of additional mobile technologies (e.g. flotation, magnetic separation,
124 centrifugal gravity separation, etc.) may be necessary to achieve an efficient recovery of metal-
125 bearing minerals other than cerussite.

126 {Figure 1}

127

128

129 *2.2 Goal and scope definition*

130 The framework for LCA includes the steps of goal and scope definition (this section 2.2), inventory
131 analysis (section 2.3), impact assessment and results interpretation (section 3; EC-JRC, 2010). The
132 goal of this LCA study is to assess the cradle-to-gate environmental performance of the SOSO mining
133 approach, using its pilot-scale application at the Olovo site as a case study. The functional unit is set
134 as “the production of one tonne of Pb concentrate, with a Pb-content of 58.7%”. The system
135 boundaries (see Figure 1) include the direct emissions to air and water generated both by the process
136 and by the subsequent process waste (tailings) on-site management; production and consumption of
137 ancillary materials (in this case, electricity and flocculants); production, transport (from site to site)
138 and maintenance of the infrastructures. The downstream treatment of the Pb-concentrate,
139 acknowledged to be potentially relevant on an environmental perspective, is however out of the
140 scope of this cradle-to-gate study which focuses on the application of the SOSO approach.

141 In this study, 13 impact categories are considered, applying the European EF Life Cycle Impact
142 Assessment Method (EF method 2.0; Fazio et al., 2018) as implemented in the SimaPro LCA software
143 (version 9), namely: climate change; acidification terrestrial and freshwater; eutrophication
144 terrestrial; eutrophication marine; eutrophication freshwater; respiratory inorganics; photochemical
145 ozone formation; cancer human health effects; non-cancer human health effects; ecotoxicity
146 freshwater; water scarcity; resource use, minerals and metals; and resource use, energy carriers.
147 Among the 16 impact categories of the EF method 2.0, three are therefore disregarded in this study,
148 due to the lack of data specific to the case study (land use) and for the sake of conciseness in results
149 interpretation (ozone depletion and ionising radiation).

150

151 *2.3 Life Cycle Inventory*

152 The foreground system under study (i.e. the process chain applied in Olovo) is modelled by use of
153 primary data drawn from the on-site pilot tests, completed with additional calculations (including
154 process simulation with USIM-PAC® software), scenarios (regarding energy), and some generic data
155 and assumptions. These primary data, described in the following sections, have led to the
156 compilation of a full inventory of input and output exchanges with the technosphere and the
157 environment (see the Supporting Information document 1 for the complete set of data and
158 associated metadata). Moreover, the background system (upstream and downstream the pilot plant)
159 is modelled considering secondary data from the ecoinvent v3.5 database, using the cut-off system

160 model (Weidema et al., 2013; ecoinvent centre, 2019). The obtained Life Cycle Inventories (LCIs)
161 have been implemented in SimaPro v9 for subsequent Life Cycle Impact Assessment (LCIA)
162 calculations.

163 2.3.1 *Process simulation for mass and water balances calculation*

164 The USIM-PAC® software (Brochot et al., 2002) has been used to compute the mass balance of the
165 plant and simulate its performance by describing the behaviour of the processed material. The
166 mineral processing simulation relied on a complete flowsheet design, combined with a material
167 model definition and several models of unit operations adjusted on experimental data. The
168 flowsheet of the simulator describes the process as unit operations linked one to each other with
169 material streams. Calibration of predictive mathematical models for each mineral processing unit
170 operation is mandatory to accommodate metallurgical variability, and to provide reliable results.

171 Pilot-scale test works of the gravity separation module included, for each material stream: flowrates
172 measurement (solid and/or slurry throughput), solid content determination in slurry and sampling of
173 solid material for further analysis (particle size distribution, chemical analysis, mineral liberation).
174 Building on these raw, on-site, measured data, coherent mass balances have been completed using
175 the reconciliation algorithm in USIM-PAC®. In other words, estimates have been recalculated for
176 each of the data points relative to total mass, element (Pb) and water balances, by using the mass
177 balance identities along the process chain (Table 1 and Figure 1).

178 Three flowrates (corresponding to the output from the selective miner, and to the flows treated
179 respectively within the comminution and gravity separation modules) have been set as fixed in the
180 reconciliation procedure. Firstly, on-site tests of the selective miner showed a performance rate
181 ranging between 13 and 24 tonnes/hour of cut material in conditions similar to those at the Olovo
182 pilot site. In a conservative approach, supported by the expert opinion of the selective miner
183 developer (Metal Innovations UK), the output flow rate was set to 15 tonnes/hour in this study, 4.25
184 hours a day (of which 3.75 hours actually enable selective extraction for a Run-of-Mine). Secondly,
185 the flows treated within the comminution and gravity separation modules were set to 5 tonnes/hour.
186 This corresponds to the capacity rate tested in Olovo regarding the comminution module and to the
187 design capacity of the gravity separation module.

188 In contrast, both the output flow rates of concentrate and tailings (from the gravity separation step)
189 and the concentration in Pb in all the input and output flows (ore, concentrate and tailings) have
190 been i) analysed based on samples collected on-site and ii) recalculated through process simulation
191 (estimates used in the LCI; Table 1 and Figure 1).

192 {Table 1}

193

194

195 2.3.2 *Energy consumption*

196 Regarding most of the operations implemented in the SOSO approach, the energy consumption is
197 calculated based on the power requirement specifications of each equipment (i.e. nominal power in
198 kW) and on their corresponding duration of operation at the pilot plant to ensure a continuous
199 operation (Braun, 2019). This approach is applied to quantify the energy required for comminution,
200 gravity beneficiation, tailings management, dewatering and, additionally, for a “base load”
201 corresponding to the electricity consumption related to offices, workshops, lighting, etc. (Table 2).
202 This quantification based on the power requirement specifications is expected to result in the
203 overestimation of the actual energy consumed on-site. On the contrary, in the specific case of the
204 selective miner, the actual power requirement (power draw) has been measured on-site (Table 2).

205 {Table 2}

206

207 During the Olovo pilot tests, the electricity was produced by the use of diesel generators. The latter
208 offer a number of advantages such as flexibility, reliability, low investment costs, etc., which explain
209 their large-scale use in (often remote) mining operation sites (Braun, 2019). The corresponding diesel
210 consumption per kWh of electricity is set to 0.25 litre, as a proxy based on technical sheets (FW
211 Power, 2018) and the expert opinion of the engineers operating the plant. Moreover, the associated
212 emissions to the environment are derived from the generic ecoinvent dataset for diesel generators
213 operation (ecoinvent centre, 2019).

214 Despite poor implementation so far, a number of parameters favour the use of renewable energy
215 systems in the electricity supply of remote mining operations: strong oil price fluctuations, increased
216 environmental awareness and falling prices for renewable energy systems (Braun, 2019; Sitorus and
217 Brito-Parada, 2020). Accordingly, the implementation of a renewable electricity system as a
218 substitute for the diesel-based electricity generation is additionally considered in a scenario analysis.
219 The corresponding containerised renewable system design is selected based on simulation
220 performed for the energy demand scenario presented in Table 2 using the software tool HOMER Pro
221 (Paneri and Yan, 2020; Paneri et al., 2021). The optimum renewable energy system configuration
222 obtained through the simulation includes solar photovoltaics (PV) and biomass-based electricity
223 generation systems, lithium-ion batteries and converters. The main characteristics of this proposed
224 renewable electricity generation system for the Olovo site are presented in Table 3, with

225 complementary information available in the SI document 2. No specific data were available for the
226 modelling of this system in a life cycle perspective, including both on-site emissions (from the
227 biomass generator) and upstream/downstream emissions and consumption of resources (e.g.
228 associated with PV panels production). Accordingly, generic datasets from the ecoinvent database
229 have been primarily used as a proxy, modified to the configuration simulated for the case of Olovo (SI
230 document 2). In particular, the PV system rated capacity has been set as in Table 3.

231 {Table 3}

232

233 2.3.3 *Modular equipment and its transport*

234 The LCI modelling includes the upstream impacts associated with the production of the modular
235 equipment used at the Olovo pilot plant. The masses and composition of equipment have been
236 mainly drawn from the documentation associated with their shipping from the United Kingdom and
237 France (place of development) to Bosnia-Herzegovina (place of pilot tests) during the course of the
238 IMP@CT project (Fitzpatrick and Moradi, 2019). The shipping information provided a detailed set of
239 data regarding the total masses of equipment used at each stage (selective miner, comminution
240 module, gravity separation module, water filtration and settling pond) and regarding some of the
241 corresponding compositions (gravity separation and tailings facility). However, only an approximate
242 set of data was available regarding the composition of the selective miner and of the comminution
243 module, therefore requiring complementary assumptions (see Table 4 and SI document 1).

244 {Table 4}

245

246 The lifetime of each module, and the annual requirement for their maintenance (e.g. regarding the
247 liner of the crusher for the step of comminution) have been set in % of total mass annually replaced
248 considering an estimator's guide from the mining sector (CostMine, 2018) complemented with
249 expert judgement (SI document 1). Finally, the (potential) on-site project lifetime has been set to 3
250 years as an assumption, from which the total Pb concentrate produced has been deduced. The use of
251 equipment, in mass terms and by type of materials the equipment is made of, has accordingly been
252 reported by tonne of Pb concentrate produced (SI document 1).

253 The modules of the SOSO approach are intended to be transported from one site to another, by
254 truck. A distance of 125 km is assumed as an average of future operating conditions. This
255 corresponds to the distance between the two pilot sites tested in the course of the IMP@CT project,

256 respectively the Olovo site and the Zajača site (Serbia). Finally, at this stage of development, no
257 information exists on the potential for recycling or reuse of the equipment. Considering their
258 composition (mostly steel), a relatively high but still conservative rate of recycling at end-of-life (80%)
259 is considered as a proxy.

260 *2.3.4 Direct emissions from the plant, including tailings*

261 The selective mining and subsequent comminution, as well as on-site hauling, generate dust
262 emissions. In the absence of site-measurements available to estimate the mass of dust emitted per
263 tonne of concentrate, the corresponding emission factors have been drawn from the ecoinvent
264 database as a proxy (ecoinvent centre, 2019, see SI document 1).

265 Moreover, the SOSO approach applied in Olovo generates two types of tailings: respectively, fine
266 tailings (disposed of in a pond), and coarse tailings (stockpiled; Figure 1). The proportion of sulfidic
267 minerals in Olovo tailings is very low due to the predominant carbonate mineralogy of the Olovo
268 deposit. The high percentage of carbonate (acid-consuming) minerals implies the neutralisation of
269 any sulfuric acid that may be produced (personal communication with Marjan Knobloch, 2020).
270 Therefore, the ecoinvent dataset for “non-sulfidic tailings disposal”, which considers no emissions
271 from tailings to the environment, is used in this study (ecoinvent centre, 2019). In addition, based on
272 expert opinion, 150 grams of anionic polyacrylamide flocculant are considered to be consumed per
273 dry tonne of tailings in order to maintain process water quality.

274

275

276 **3 Results and discussion**

277

278 *3.1 Total impacts and contribution analysis*

279 The production of one tonne of Pb concentrate, with a Pb-content of 58.7%, implies the potential
280 generation of 897 kg CO₂-eq (climate change), 6.27 kg NMVOC-eq (photochemical ozone formation)
281 and 5.37 mol H⁺ eq (terrestrial and freshwater acidification), and in the meantime the potential use
282 of 13,025 MJ of energy resources. The complete overview of impacts, distinguishing 13 impact
283 categories, is provided in Table 5.

284 {Table 5}

285

286 The base load and the gravity separation step represent, respectively, 36%-38% and 35%-36% of the
287 total impacts regarding seven impact categories: climate change, photochemical ozone formation,
288 respiratory inorganics, acidification terrestrial and freshwater, eutrophication marine, eutrophication
289 terrestrial and resource use, energy carriers (Figure 2). The remaining contribution (26%-29%) is
290 shared among selective mining (15%-16%) and, to a lower extent, comminution and tailings
291 management. The consumption of electricity, supplied by on-site diesel generators, globally
292 contributes to 89%-95% of the impacts associated with these seven impact categories (Figure 3). The
293 share in impacts of each process step is directly related, and overall very similar, to the share in the
294 total consumption of electricity. In particular, “base load and dewatering”, “gravity separation” and
295 “selective mining” represent, respectively, 41%, 34% and 16% of the total consumption of electricity
296 per tonne of concentrate (Table 2), in line with their contribution to the total impacts (Figure 2). In
297 the specific case of base load and dewatering, the impact is entirely due to the consumption of
298 electricity. On site facilities (offices, shops, storage, laboratories) represent the largest share of
299 electricity consumption and therefore of impacts (28%-30% of the total impacts per tonne of Pb
300 concentrate), while lighting (6%) and dewatering (3%) represent more limited shares.

301

302 {Figure 2}

303 {Figure 3}

304

305 Moreover, regarding four other impact categories (cancer human health effects; ecotoxicity,
306 freshwater; eutrophication, freshwater; and water scarcity), gravity separation stands for 49% to 58%
307 of the impacts per tonne of concentrate. In relation to cancer human health effects, ecotoxicity
308 (freshwater) and eutrophication (freshwater), gravity separation requires the largest mass of
309 equipment (Table 4) with the lowest lifetime (SI document 1), implying a large contribution
310 compared to other process steps. Similarly, comminution represents a relatively large contribution –
311 despite lower than that of gravity separation – regarding these three impact categories (from 16% to
312 22%), also mainly associated with the use of equipment. Overall, still considering these three impact
313 categories, equipment (from 50% to 67% of the total impacts per tonne of concentrate) and, to a
314 lower extent, electricity consumption (30% to 46%) make important contributions. In contrast, for
315 the specific case of water scarcity, electricity consumption is the main contributor (48% of the total).
316 The direct consumption of water in the gravity separation step also represents an important
317 contribution (33% of the total), which adds to the impact of electricity consumption, subsequently
318 driving the major contribution of gravity separation among all the process steps (Figure 2).

319 Finally, regarding the two remaining impact categories (resource use, minerals and metals, and non-
320 cancer human health effects), the direct exchanges with the environment drive the impact. Firstly,
321 the impact on resource use, minerals and metals, is almost entirely (more than 99.9%) associated
322 with the extraction of lead at the Olovo mine, in the selective mining step. Secondly, regarding non-
323 cancer human health effects, lead emissions to air represent a major share of the impact (80%). In
324 this study, emissions of lead as well as emissions of dust have been modelled considering secondary,
325 literature-based, datasets. These emissions have been associated with the step of comminution in
326 the presentation of results (Figure 2) but are in fact also partly induced by selective mining and
327 hauling.

328

329 *3.2 Discussion*

330

331 *3.2.1 Potential of the SOSO approach for reducing the environmental impacts of mining and* 332 *beneficiation activities*

333 The environmental performance of the SOSO approach, and more generally of mining and
334 beneficiation activities, is context-specific. It depends in particular on the type of ore extracted (at a
335 given grade, considering a given mineralogy), on the main concentrate produced (at a given grade),
336 on the potential co-productions, on the exchanges with the technosphere and their environmental
337 impacts, etc. Therefore, the results of this study cannot be comprehensively compared with the
338 environmental performance of lead concentrate as found in the literature of LCA studies. The latter,
339 however, may be particularly insightful regarding the extent to which the SOSO approach can enable
340 mining operators to tackle some of the key environmental hotspots identified regarding the cradle-
341 to-gate production of lead concentrates.

342 Firstly, in the case of a lead-zinc mine located in the Guangdong province of China, Tao et al. (2019)
343 report that the underground mining represents more than half of the impacts regarding a number of
344 impact categories including climate change, terrestrial acidification, marine eutrophication,
345 photochemical oxidant formation, particulate matter formation, and fossil depletion impact
346 categories. Similarly, in the ecoinvent v3.5 database, the step of blasting induces 62% to 83% of the
347 impact of a lead concentrate production, regarding five impact categories out of the 16 of the EF 2.0
348 impact assessment method: photochemical ozone formation, respiratory inorganics, acidification
349 terrestrial and freshwater, eutrophication marine and eutrophication terrestrial (ecoinvent centre,
350 2019; calculations performed with SimaPro version 9). In contrast, the contribution of the mining

351 step to the total burden is far more limited using a SOSO approach. Indeed, the SOSO approach
352 involves selective extraction of the ore, accordingly avoiding the use of explosives and limiting the
353 energy consumption of the mining step (and of the subsequent comminution and grinding steps,
354 thanks to the already fine granularity obtained from the selective miner).

355 The use of chemicals in the exploitation of targeted deposits is a particularly useful metric for
356 comparison of SOSO and conventional approaches. For example, Tao et al. (2019) report that the
357 consumption of copper sulfate in the beneficiation chain of a lead-zinc sulfidic ore is an important
358 contributor to a number of impact categories (human toxicity, ecotoxicity, freshwater
359 eutrophication). Where the SOSO approach targets small deposits that are high-grade, beneficiation
360 can rely more heavily on gravity-based separation processes, therefore limiting the use of chemicals
361 and the potentially important impacts that they generate, upstream in the life cycle. Thus, the
362 limited use of chemicals in the SOSO exploitation of the targeted deposits is beneficial to the
363 environmental performance of the concentrate production.

364

365 *3.2.2 On the contribution of electricity consumption, and the potential for its reduction*

366 Electricity consumption represents an important share of the impacts associated with the production
367 of Pb concentrate. This implies that any ambition to reduce the environmental impacts of the SOSO
368 approach should target, as a first priority, the electricity *demand* and *supply*.

369 On the *demand* side, the results firstly highlight that measures to reduce electricity consumption and
370 its associated environmental impacts should not be limited to the process chain, but should instead
371 consider the whole mine in a holistic perspective, including the electricity consumption associated to
372 ancillary equipment. The quantification of the actual impact of these ancillary consumptions would
373 require a refined approach based on site-measurements. This would create opportunity for potential
374 impact reduction thanks to e.g. a different organization of the mine. As the most electricity
375 demanding process operation steps, gravity separation and to a lower extent selective mining would
376 be subject to particular scrutiny in attempts to reduce the environmental impacts of the SOSO
377 approach.

378 In most cases in this study, values of energy consumption were estimated considering nominal power
379 rather than power draw. This implies that the impact assessment results correspond to the “upper
380 bound” of impacts: a lower electricity consumption, and subsequently lower impacts, can be
381 expected based on site-measured data. For example, the electricity consumption associated with the
382 selective miner is dependent on the ore crushability, which varies from site to site as a function of

383 the ore extracted. In this study, the measured value used in the modelling (1.7 kWh/tonne of Run-of-
384 Mine) is less than half of the value based on the nominal power.

385 On the *supply* side, when implementing a diesel generator as during the Olovo pilot tests, diesel
386 consumption is a key parameter, so far only estimated based on technical sheets as a proxy and
387 therefore still uncertain. Considering the seven impact categories for which the diesel-based supply
388 of electricity is the key driver of impacts (climate change, photochemical ozone formation,
389 respiratory inorganics, acidification terrestrial and freshwater, eutrophication marine, eutrophication
390 terrestrial and resource use, energy carriers), a 10%-lower consumption of diesel (0.225 litre/kWh
391 rather than 0.25 litre/kWh) would imply impacts around 9% lower. Therefore, the efficiency of the
392 diesel generator (in litre diesel/kWh) is an important lever to be further investigated and improved in
393 order to reduce the environmental impacts of the SOSO approach. Moreover, the implementation of
394 a renewable electricity mix as described in Table 3 and in the SI document 2 is also a potential option
395 for environmental impact reduction. It leads to lower impacts regarding eight impact categories out
396 of the 13 under study (Figure 4). In particular, the impact of Pb concentrate production would
397 potentially amount to 201 kg CO₂-eq per tonne of concentrate, which is 78% lower than in the diesel-
398 based reference scenario. Important impact reductions are also observed regarding resource use,
399 energy carriers (-79%), eutrophication terrestrial and eutrophication marine (-60%), photochemical
400 ozone formation (-59%), acidification terrestrial and freshwater (-58%), and respiratory inorganics (-
401 47%). However, the impacts associated with Pb concentrate production are notably larger regarding
402 three impact categories: eutrophication, freshwater (18% larger), ecotoxicity, freshwater (26%) and
403 non-cancer human health effects (47%). Therefore, a renewable electricity mix globally enables a
404 reduction in impact for most impact categories but there are some trade-offs. This is mainly due to
405 the PV plant, which contributes to 86% of the impact of electricity supply regarding eutrophication
406 freshwater (mainly due to the use of reagents in the production of PV cells), and to the biomass
407 generator, which contributes to 73% and 92% of the impact of electricity supply on ecotoxicity
408 freshwater and non-cancer human health effects (mainly due to the management of ashes and to
409 direct air emissions from combustion). The modelling of the renewable electricity mix is based on a
410 scenario, supported by secondary datasets to model the LCI, not site data. The use of site-specific
411 (primary) datasets is an important perspective to refine the quality of the modelling and of the
412 associated impact assessment results.

413 {Figure 4}

414

415

416 *3.2.3 On the contribution of equipment: CAPEX do not only influence the economic evaluation*

417 The integrated mobile equipment is the main innovation in the SOSO concept. Whereas many LCA
418 studies neglect the production of capital goods (CAPEX) necessary to manufacture a good, in this
419 study equipment (primarily metal-based) is a relatively important contribution to the impacts
420 regarding three impact categories: cancer human health effects; ecotoxicity, freshwater; and
421 eutrophication, freshwater. These results are in line with those of Frischknecht et al. (2007) who
422 observed that freshwater ecotoxicity and human toxicity are more sensitive towards an inclusion or
423 exclusion of capital goods in the LCA of products and services, compared to other impact categories.

424 As a consequence, the parameters associated with the use of equipment, such as mass (as presented
425 in Table 4), nature of the materials the equipment is made of, lifetime, etc., have an important
426 influence on the impact of the SOSO approach regarding these impact categories. For example, if the
427 comminution and gravity separation modules are fabricated from only unalloyed steel, instead of
428 containing low-alloyed steel, then the impact of Pb-concentrate production is reduced by 16% to 38%
429 regarding the three impact categories eutrophication, freshwater, ecotoxicity, freshwater and cancer
430 human health effects.

431 However, it is to be noted that there is still some uncertainty in the modelling of both the foreground
432 (primary data of composition) and the background (LCIs of metals) datasets associated with the
433 equipment. More generally, the uncertainty associated with data on infrastructure in LCA, for
434 example in the ecoinvent database through the basic uncertainty factors, is usually larger than that
435 of other economic exchanges (such as energy, material or transport for example; Weidema et al.,
436 2013; Muller et al., 2016). Whereas the mine operator has the ability to directly act on the impact
437 source in the case of electricity demand and supply, the main levers to reduce the impact
438 contribution of equipment are more specifically under the responsibility of other operators upstream
439 in the life cycle.

440

441

442 *3.2.4 On the contribution of tailings management: site-specific considerations and general modelling*
443 *issues*

444 In the ecoinvent dataset for non-sulfidic tailings disposal, no emissions from the tailings to the
445 environment are accounted for. However, environmental tests on sample material from the Olovo
446 mine site were carried out, which showed relatively elevated lead concentrations (up to 200 mg/l;
447 personal communication with Marjan Knobloch, 2020) in waters generated from tailings materials.

448 Long term studies are necessary to evaluate the water quality from tailings and to conduct an
449 environmental risk assessment for these. The management of tailings was not identified in the LCIA
450 results as a hotspot, as a function of the dataset used and under the assumption that the
451 construction of the tailings pond complies with the latest and best technical knowledge.
452 Nevertheless leaks and failures could entail a risk of impact on human health and ecotoxicity in a
453 context of missing long term environmental risk studies. Tailings management should therefore be
454 considered as an unquantified risk in the case of industrial implementation of the SOSO approach in
455 Olovo or other places.

456 Fine tailings generated using the SOSO approach still contain about 5% of Pb, which is close to the
457 lead content in the Run-Of-Mine (5 to 6% Pb). This means that only low recovery of fine cerussite (i.e.
458 below 63 microns) is achievable so far. Thus, SOSO-compatible ways of improvement for the
459 recovery of fine cerussite, such as centrifugal gravity separation, are to be investigated in order to
460 maximize lead recovery using the SOSO approach. At the same time, such improvement will reduce
461 the deportment of lead towards the tailings pond, and in a certain extent towards the environment.
462 Mineral processing optimization holds the key to resource efficiency and low-impact tailings
463 management.

464 This conclusion particularly holds in the context of the exploitation of sulfidic minerals, inducing the
465 subsequent generation and disposal of sulfidic tailings. As a sensitivity analysis, the SOSO approach is
466 considered to be applied to a sulfidic mineral ore, instead of a non-sulfidic ore as in Olovo. By
467 assumption, the amount of tailings generated per tonne of concentrate produced is set equivalent to
468 that of the Olovo case study, and the corresponding leachate emissions to the environment are
469 modelled based on the associated ecoinvent dataset (ecoinvent, 2019; Doka, 2008). The disposal of
470 sulfidic tailings, instead of non-sulfidic tailings, overall implies a larger impact of Pb concentrate
471 production by a factor of 2 regarding ecotoxicity, freshwater, and a factor of 72 regarding
472 eutrophication, freshwater. The management of tailings is thus reinforced as a potential issue for the
473 environmental performance of the SOSO approach, especially where sulfidic ores are exploited. A
474 more refined quantification would be necessary to precisely evaluate to what extent, and in which
475 contexts of tailings characteristics (including mineralogy) and disposal techniques, the disposal of
476 tailings is actually a key environmental hotspot. Promising developments are currently on-going
477 regarding the estimation of releases from mine tailings to the environment for their integration into
478 LCA calculations, for example by implementing reactive transport modelling to account for local
479 characteristics (Muller et al., 2019).

480

481 *3.2.5 On the contribution of the SOSO approach to resource accessibility, and depletion*

482 The Abiotic Depletion Potential (ADP) is the characterization approach used to calculate the impact
483 associated with minerals and metals resource use in the EF 2.0 method. It is based on the concept of
484 depletion: the extraction of a resource from the Earth's crust, which implies the reduction of the
485 corresponding geological stocks, is considered to contribute to this resource depletion. In this LCA
486 study, more than 99.9% of the impact on minerals and metals resource use is due to the extraction of
487 Pb from the ground (hotspot elementary flow) in the selective mining step (hotspot process).

488 In the inventory, the extraction of resources from the ground is recorded as the amount of target
489 material that is contained in the ore (1,376 kg of lead extracted from the ground per tonne of lead
490 concentrate produced), similarly to the approach implemented inecoinvent 3 (Weidema et al.,
491 2013). The impact assessment approach considers that this whole quantity contributes to resource
492 depletion, disregarding the contribution of the SOSO approach to the increase in resource
493 accessibility. This is a key limit in a context where the Task Force "Mineral Resources" of the United
494 Nations Environment Programme and SETAC (UNEP-SETAC) "Life Cycle Initiative" defines the
495 safeguard subject for "mineral resources" as "the potential to make use of the value that mineral
496 resources can hold for humans in the technosphere" (with the associated damage "quantified as the
497 reduction or loss of this potential caused by human activity"; Berger et al., 2020). Indeed, firstly, the
498 SOSO approach may enable the exploitation of currently not economically viable deposits, i.e.
499 rendering metals in the geological stocks more accessible. It is noteworthy that, at least regarding
500 the 587 kg of lead transferred from the ground to the concentrate (i.e. 43% of the total lead
501 extracted from the ground), the SOSO approach does not reduce – but instead increases - the
502 potential "to make use of the value" of a metal in the ground (lead in Olovo) that is currently not
503 economically exploitable. This is a key beneficial aspect of the SOSO approach regarding the
504 safeguard subject for "mineral resources", that has even justified the investments made for the
505 development of such a solution, but that is not covered in the impact assessment results presented
506 in this article. Moreover, the transfer of lead from the ground to the concentrate thanks to the SOSO
507 approach makes it available in the technosphere for the production of refined lead (potentially used
508 in several life cycles of products). The indicator of impact on minerals and metals resource use
509 accordingly does not account for the fact that 43% of the lead extracted (587 kg per tonne of
510 concentrate) are transferred to the concentrate and made more valuable, more easily accessed for
511 use in the economy, than originally in the ground. Accordingly, the SOSO approach applied in Olovo
512 enables to increase the potential to make use of the value that lead can hold for humans in the
513 technosphere, which is not addressed in the impact assessment.

514 Moreover, the “depletion-based” impact assessment approach also has major implications on the
515 contribution analysis and the subsequent eco-design actions that it may support. The 43% of lead
516 transferred to the concentrate are part of the functional unit, and therefore constitutes the lower
517 boundary of impact on minerals and metals resource use in this case study. Indeed, regarding each
518 tonne of concentrate produced, it is impossible to extract less than 587 kg of lead from the ground.
519 Therefore, effective actions to reduce the impact of the Pb concentrate production on minerals and
520 metals resource use should focus on the remaining 57% of lead not transferred to the concentrate,
521 but instead “lost” or “dissipated” along the cradle-to-gate production. Recent developments in the
522 LCA field aim to account for these losses (contribution to resource dissipation), rather than for the
523 extraction of mineral resources from the ground (contribution to resource depletion; Beylot et al.,
524 2020a; 2020b; 2021; Charpentier Poncelet et al., 2019). In particular Beylot et al. (2020a; 2021)
525 suggest to report the dissipative flows of mineral resources, in mass units, at the unit process level
526 (that is, at the level of the “smallest element considered in the life cycle inventory analysis for which
527 input and output data are quantified”; EC-JRC, 2010). In the case of the SOSO approach applied to
528 the Olovo site, the coherent mass balance enables analysts to precisely trace the 57% of lead
529 extracted from the ground and further dissipated along the cradle-to-gate concentrate production
530 process-chain (43% in the fine tailings and 14% in the coarse tailings). For example, following the
531 approach suggested by Beylot et al. (2021), and considering their so-called “short-term perspective”,
532 these flows can reasonably be assumed to be “not accessible to future users” (i.e., dissipative) and
533 may therefore be reported as dissipative flows of mineral resources in the LCI. This 57% damages the
534 safeguard subject for “mineral resources” (“the potential to make use of the value that mineral
535 resources can hold”). That is to say, this is the fraction of resources extracted from the ground
536 responsible for the impact on minerals and metals resource use, which should be targeted in any
537 future attempt to reduce the impact of the SOSO approach. Process simulation along the cradle-to-
538 gate process chain of metals production enables the calculation of balanced mass data for resource
539 flows (as implemented in this study) and of associated parameters (in particular concentration and
540 mineralogy). This is of potential interest to further assess the accessibility of these resources to any
541 potential future users, in a time-horizon to be defined. Process simulation accordingly appears well-
542 adapted to support the quantification of resource dissipation in the LCI and subsequently provide
543 relevant information on associated key hotspots.

544

545 **4 Conclusions and perspectives**

546 The SOSO mining approach, developed to exploit the valuable deposits that are not amenable to
547 large-scale mining operations, in particular in Europe, i) avoids the use of explosives and limits the
548 energy consumption of the mining step thanks to the selective extraction of the ore, and ii) limits the
549 use of chemicals and the potentially important impacts that they generate, upstream in the life-cycle.
550 Any further improvement of the environmental performance should build on some of the
551 opportunities identified in this study, with focus on its deployment at a pilot-scale in Bosnia-
552 Herzegovina. Firstly, the base load and the gravity separation step represent the largest contributions
553 regarding seven impact categories out of the 13 under study, mainly due to their associated
554 electricity consumption. Therefore, any targeted reduction in impacts should prioritize measures on
555 electricity demand and supply. In particular, the implementation of a renewable electricity mix,
556 instead of the diesel-based generation of electricity as classically implemented in mining and
557 concentration activities, creates space for improvement in environmental performance despite a
558 number of trade-offs in impacts. Secondly, equipment importantly contributes to some impact
559 categories, including toxicity and ecotoxicity-related categories. However, the uncertainty in the
560 modelling on these aspects is relatively important, and some of the main levers to reduce the
561 associated impacts are more specifically under the responsibility of other operators upstream in the
562 life cycle. Thirdly, the management of tailings is a potential issue for the environmental performance
563 of the SOSO approach, especially in case of the exploitation of sulfidic ores. The integration into LCA
564 calculations of more refined quantifications of releases from mine tailings is a necessary future
565 development for a more precise assessment of mining activities, including SSM.

566 The SOSO approach includes adaptable flowsheet designs for processing different types of ores. As a
567 consequence of the site-specific flowsheets and operating conditions (e.g. ore grade, or background
568 context of the exchanges with the technosphere), the environmental performance of the SOSO
569 approach is also expected to be site-specific and variable. In this study, mass balance reconciliation
570 along the cradle-to-gate process chain of Pb concentrate production proved particularly relevant to
571 quantify the exchanges with the technosphere and the environment per tonne of Pb concentrate
572 (the functional unit), and to support the discussion relative to resource dissipation along the process-
573 chain. In the future, the adaptation and use of mineral processing simulators (such as USIM-PAC®)
574 capabilities to optimize the SOSO process chain when considering ores and processes variability
575 appears a promising step forward. Such an optimization could be performed in a holistic
576 environmental perspective, considering the coupling not only with LCA as showcased in this study,
577 but also with databases relative to primary and secondary metallic ores deposits in Europe.

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581

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716 **Tables**

717 Table 1: Application of the SOSO approach for the processing of a high-grade Pb ore at the Olovo
 718 pilot plant: total mass and Pb balances after process simulation using USIM-PAC®

| Operation module | Output flow | Material flow rate (solid phase), in tonnes/hour | Duration of operation (hours/day) | Solids concentration, in % | Pb concentration in solid phase, in % |
|--------------------|-----------------------|--|-----------------------------------|----------------------------|---------------------------------------|
| Selective miner | Selectively mined ore | 15 | 4.25* | 100 | 5.47 |
| Comminution | Processed ore | 5 | 11.25 | 96 | 5.47 |
| Gravity separation | Concentrate | 0.199 | 11.25 | 75 | 58.7 |
| | Coarse tailings | 2.49 | | 90 | 1.56 |
| | Fine tailings | 2.31 | | 25 | 5.10 |

719 *of which 3.75 hours actually enable selective extraction for a Run-of-Mine
 720

721 Table 2: Application of the SOSO approach for the processing of Pb-rich ore at the Olovo pilot plant:
 722 energy requirement per tonne of final concentrate

| Process step | Value | Unit |
|--------------------------|-------|-----------------------|
| Selective mining | 156 | kWh/tonne concentrate |
| Comminution | 54 | kWh/tonne concentrate |
| Mineral separation | 324 | kWh/tonne concentrate |
| Tailings | 31 | kWh/tonne concentrate |
| Base load and dewatering | 387 | kWh/tonne concentrate |
| Total | 952 | kWh/tonne concentrate |

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725 Table 3: Optimum renewable energy system configuration obtained from Homer PRO-based
 726 simulation for the case of Olovo (main characteristics; Paneri and Yan, 2020)

| Photovoltaics system | | Biomass generator | | Converter | | Storage | |
|----------------------|-----------------------------|-------------------|-----------------|----------------|-----------------|----------|---------------------|
| Type | Solar PV with ballast | Size | 125 kW | Type | Hybrid inverter | Type | Lithium-ion battery |
| Panel type | Flat plate mono cristalline | Capacity factor | 25% | Rated capacity | 144 kW | Lifetime | 10 years |
| Rated capacity | 438 kW | Fuel type | Solid biomass | Lifetime | 10 years | Weight | 100 kg |
| Capacity factor | 13.4% | Fuel consumption | 262 tonnes/year | | | | |
| Lifetime | 25 years | | | | | | |

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728 Table 4: Equipment used for the processing of Pb-rich ore at the Olovo pilot plant: main
 729 characteristics (see SI document 1 for a complete description by type of materials)

| | Total mass (kg) | Main materials |
|--|-----------------|---|
| Selective miner, in container | 12000 | Unalloyed and low-alloyed steel |
| Comminution, in container | 10450 | Unalloyed and low-alloyed steel |
| Gravity separation, in container | 27100 | Low-alloyed steel, and to a lower extent plastics |
| Concrete used for on-site implementation | 42000 | Reinforced concrete |

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733 Table 5: Environmental impacts induced by the production of one tonne of Pb concentrate (58.7% of
 734 Pb), distinguishing 13 impact categories (EF method 2.0)

| Impact category | Impact value | Unit |
|--|-------------------------|-------------------------|
| Climate change | 897 | kg CO ₂ eq |
| Photochemical ozone formation | 6.27 | kg NMVOC eq |
| Respiratory inorganics | 6.98 x 10 ⁻⁵ | disease incidence |
| Non-cancer human health effects | 2.88 x 10 ⁻⁴ | CTUh |
| Cancer human health effects | 2.17 x 10 ⁻⁵ | CTUh |
| Acidification terrestrial and freshwater | 5.37 | mol H ⁺ eq |
| Eutrophication freshwater | 8.18 x 10 ⁻² | kg P eq |
| Eutrophication marine | 2.07 | kg N eq |
| Eutrophication terrestrial | 22.7 | mol N eq |
| Ecotoxicity freshwater | 355 | CTUe |
| Water scarcity | 129 | m ³ deprived |
| Resource use, energy carriers | 13,025 | MJ |
| Resource use, mineral and metals | 8.72 | kg Sb eq |

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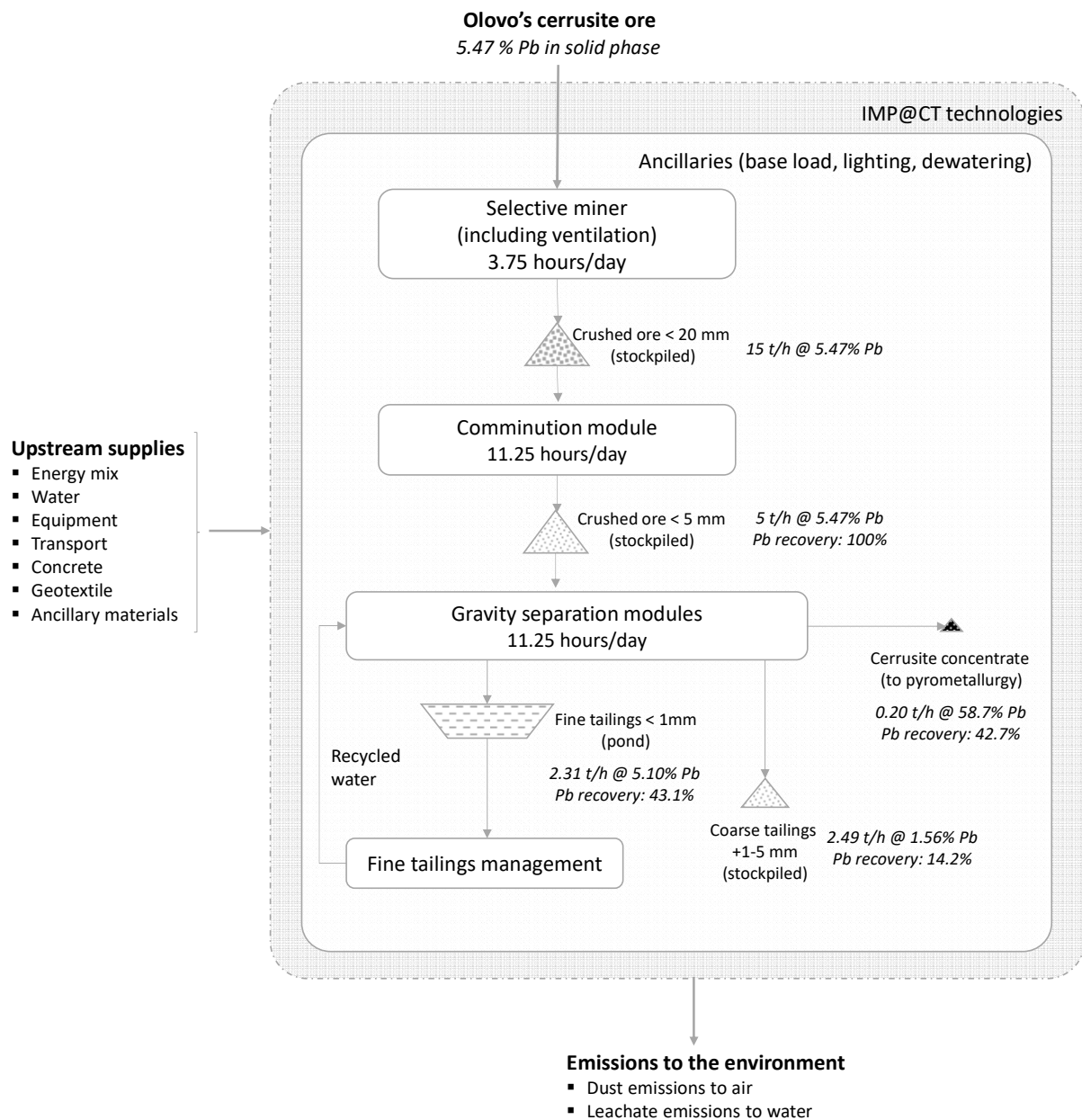
736 **Figures**

737 Figure 1: Application of the IMP@CT switch-on switch-off approach to a high-grade Pb deposit in
 738 Olovo, Bosnia-Herzegovina: system boundaries

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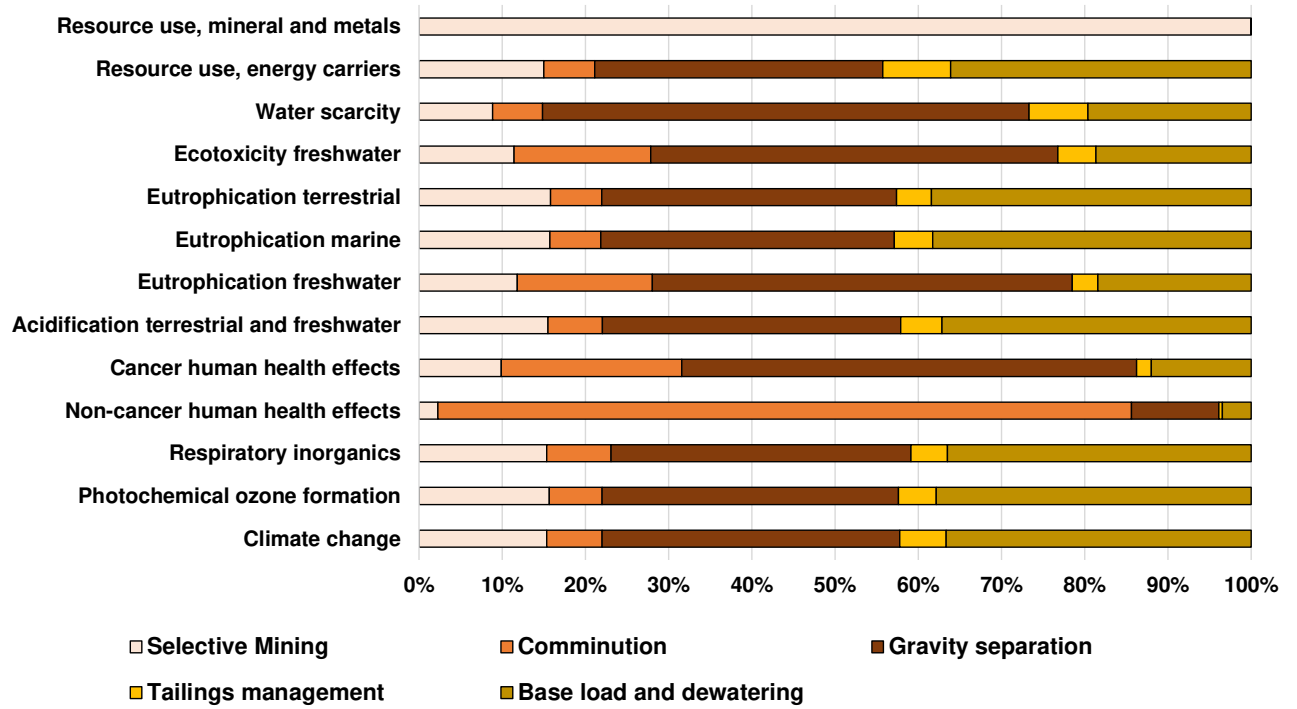
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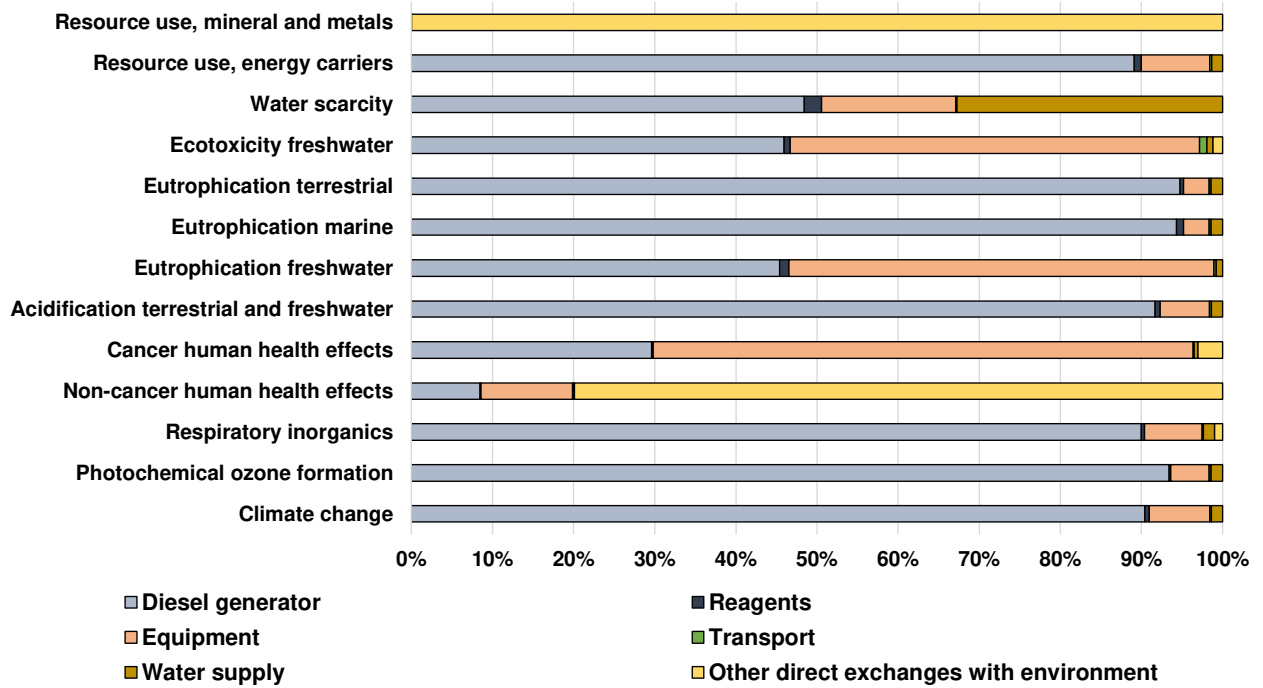
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743 Figure 2: Life cycle environmental impacts induced by the production of one tonne of Pb concentrate
 744 at the Olovo site: contributions by process steps of the SOSO approach



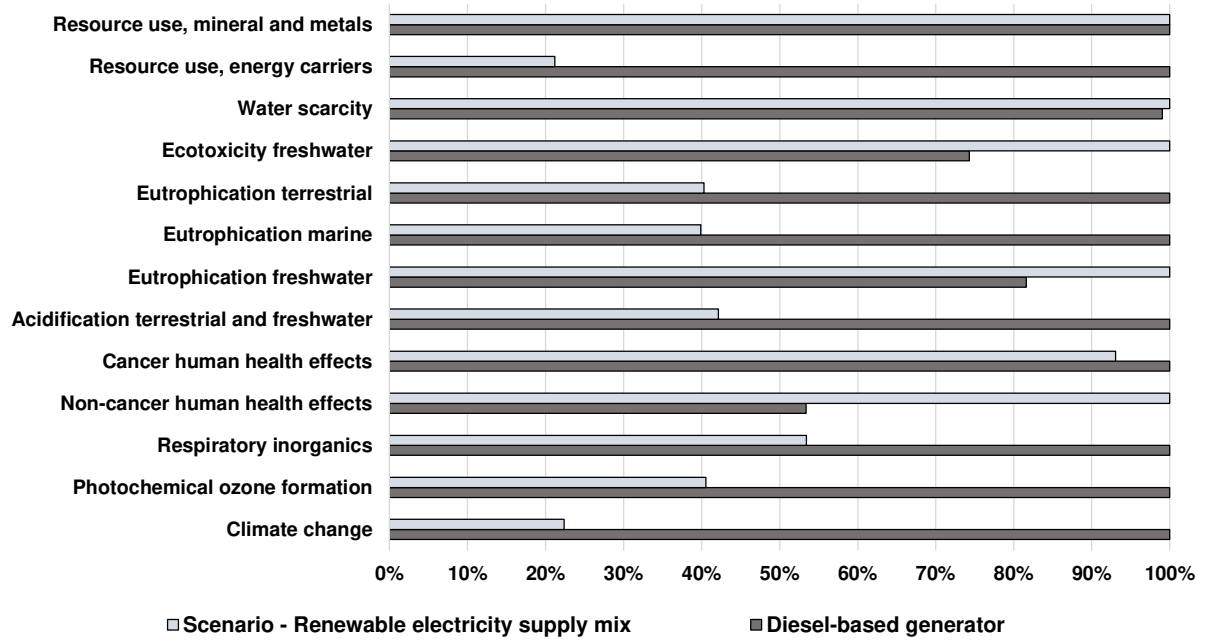
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747 Figure 3: Life cycle environmental impacts induced by the production of one tonne of Pb concentrate
 748 at the Olovo site: contributions by exchange with the technosphere and the environment



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751 Figure 4: Comparison of total life cycle environmental impacts induced by the production of one
 752 tonne of Pb concentrate at the Olovo site, in the case of diesel-based electricity supply versus
 753 renewable electricity (PV and biomass-based) supply



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