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

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## Abstract

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

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

## 1. Introduction

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

Europe has been actively mined over many centuries. Today, the exploitation of former mine sites and of small deposits, where larger mining operations may not be feasible, appears as one of the major opportunities to access raw materials in the European territory (EC, 2013). Europe has a large number of small and complex mineral deposits, particularly of critical and strategic raw materials as reported in European mineral resources databases such as ProMine or Minerals4EU<sup>1</sup> (Cassard et al., 2014; Cassard et al., 2015). However, so far, their exploitation has been considered not economically viable, due to a short life-of-mine that cannot justify large capital investment in infrastructure, and insufficient returns (Moore et al., 2020). Accordingly, new business and technology solutions are necessary to enable the small-scale mining (SSM) of these deposits, while ensuring low levels of environmental and social adverse effects (Sidorenko et al., 2020). Compared to artisanal mining, SSM in Europe will i) have higher overheads, ii) use advanced extraction and processing technologies, and iii) employ small but trained workforce (Sidorenko et al., 2020). Switch on-switch off (SOSO) is one approach to small-scale mining, which relies on modularised mobile plants, transported between sites and adaptable to the local site-conditions. In this context, the EU-funded project IMP@CT<sup>2</sup> proposed to develop a new SOSO mining approach to exploit the valuable deposits that are not amenable to large-scale mining operations. The project ended with two on-site pilot test works respectively on the lead mine of Olovo (Bosnia-Herzegovina) and on the Veliki Majdan mine for processing antimony ore from the Zajača deposit (Serbia) (Moore et al., 2020; Moore, 2019; Moore et al., 2018; Bodin et al., 2019). These two deposits are representative of a number of small deposits in Europe: moderately or extensively explored, previously mined, reasonably well-understood, and therefore potentially representing an excellent opportunity for rapid switch-on production in response to short-term changes in market forces.

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

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

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

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

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

In this context, this study aims at assessing the environmental performance of the SOSO mining approach in a life cycle perspective, considering its pilot-scale implementation on a high-grade lead 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.

## 2. Method

### 2.1 IMP@CT process-chain description

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

The IMP@CT SOSO approach can be adapted for its application to a range of small European deposits rich in elements such as lead, antimony, and other (including critical) metals (Moore, 2018). In the framework of the IMP@CT project, it has been specifically deployed at a pilot-scale to the case of a Pb-rich deposit located in Olovo (Bosnia-Herzegovina). The Olovo Pb deposit is hosted by carbonate rocks where cerussite ( $\text{PbCO}_3$ ) is the main mineral (Palinkaš et al. 2008; 2016).

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

{Figure 1}

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



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

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

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

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

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

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

{Table 1}

### 2.3.2 Energy consumption

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

{Table 2}

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

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

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

{Table 3}

### 2.3.3 Modular equipment and its transport

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

{Table 4}

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

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

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

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

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

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

### **3 Results and discussion**

#### *3.1 Total impacts and contribution analysis*

The production of one tonne of Pb concentrate, with a Pb-content of 58.7%, implies the potential generation of 897 kg CO<sub>2</sub>-eq (climate change), 6.27 kg NMVOC-eq (photochemical ozone formation) and 5.37 mol H<sup>+</sup> eq (terrestrial and freshwater acidification), and in the meantime the potential use of 13,025 MJ of energy resources. The complete overview of impacts, distinguishing 13 impact categories, is provided in Table 5.

{Table 5}

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

{Figure 2}

{Figure 3}

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

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

## 3.2 Discussion

### 3.2.1 Potential of the SOSO approach for reducing the environmental impacts of mining and beneficiation activities

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

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

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

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

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

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

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

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

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

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

{Figure 4}



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

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

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

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

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

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

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

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

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

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

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

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

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

#### 4 Conclusions and perspectives

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

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

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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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724

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						

727

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 <sub>2</sub> eq
Photochemical ozone formation	6.27	kg NMVOC eq
Respiratory inorganics	$6.98 \times 10^{-5}$	disease incidence
Non-cancer human health effects	$2.88 \times 10^{-4}$	CTUh
Cancer human health effects	$2.17 \times 10^{-5}$	CTUh
Acidification terrestrial and freshwater	5.37	mol H <sup>+</sup> eq
Eutrophication freshwater	$8.18 \times 10^{-2}$	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 <sup>3</sup> deprived
Resource use, energy carriers	13,025	MJ
Resource use, mineral and metals	8.72	kg Sb eq

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**Figures**

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

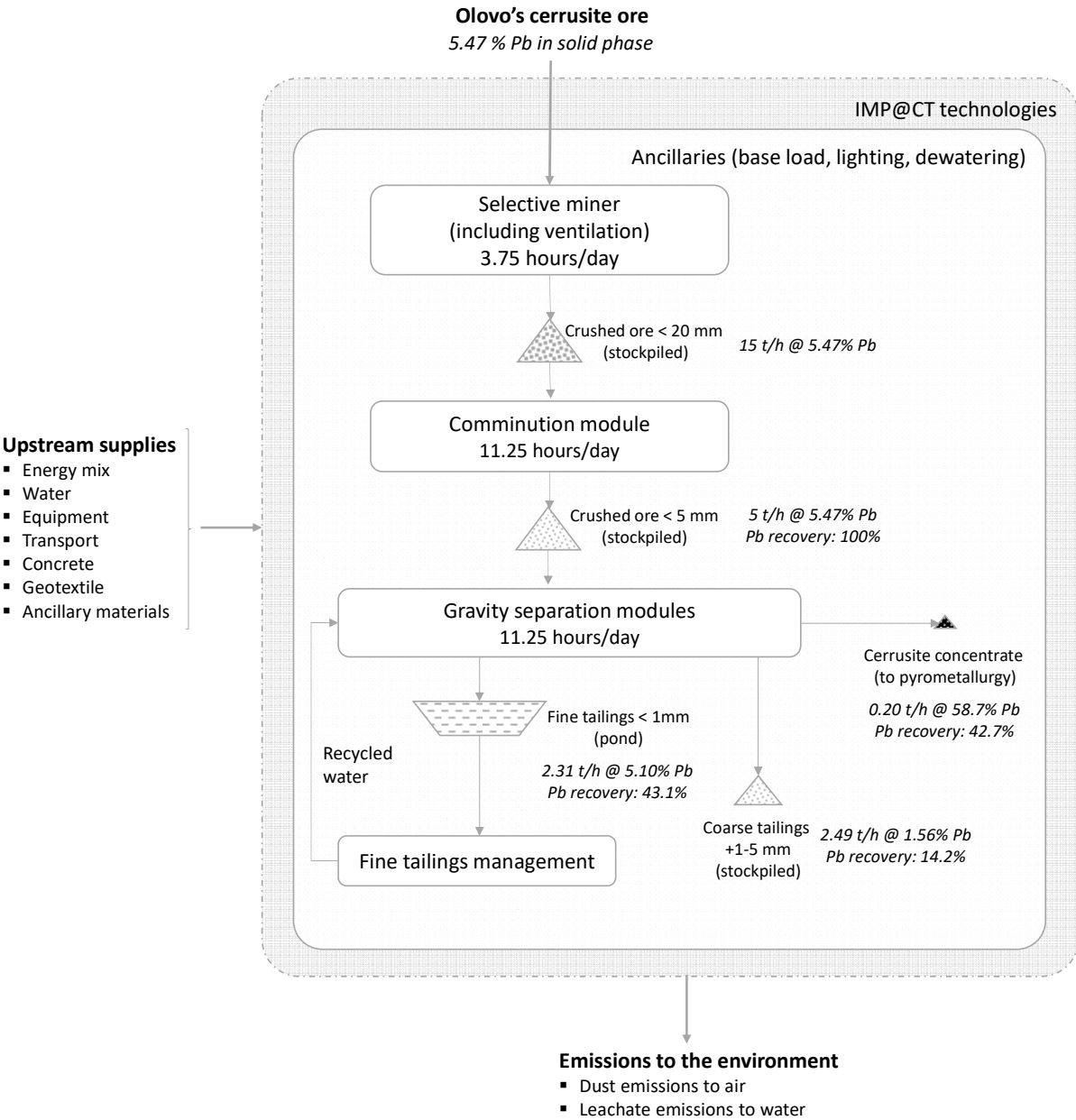


Figure 2: Life cycle environmental impacts induced by the production of one tonne of Pb concentrate at the Olovo site: contributions by process steps of the SOSO approach

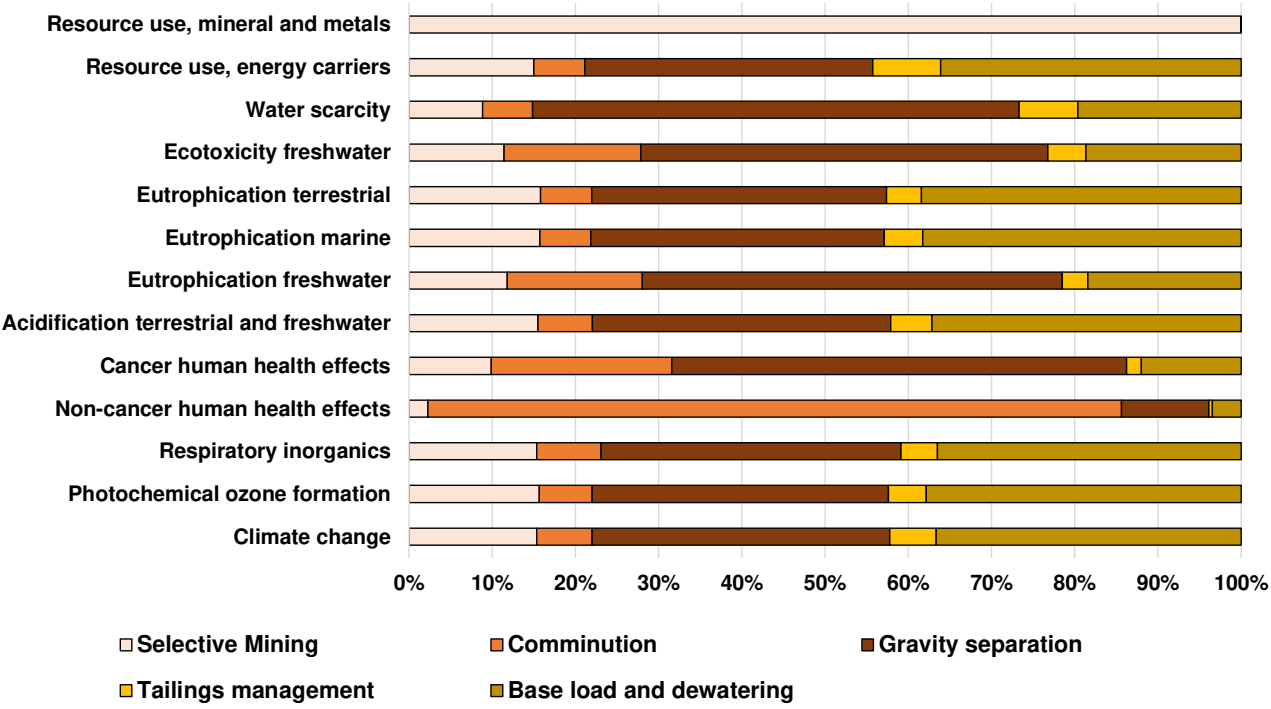
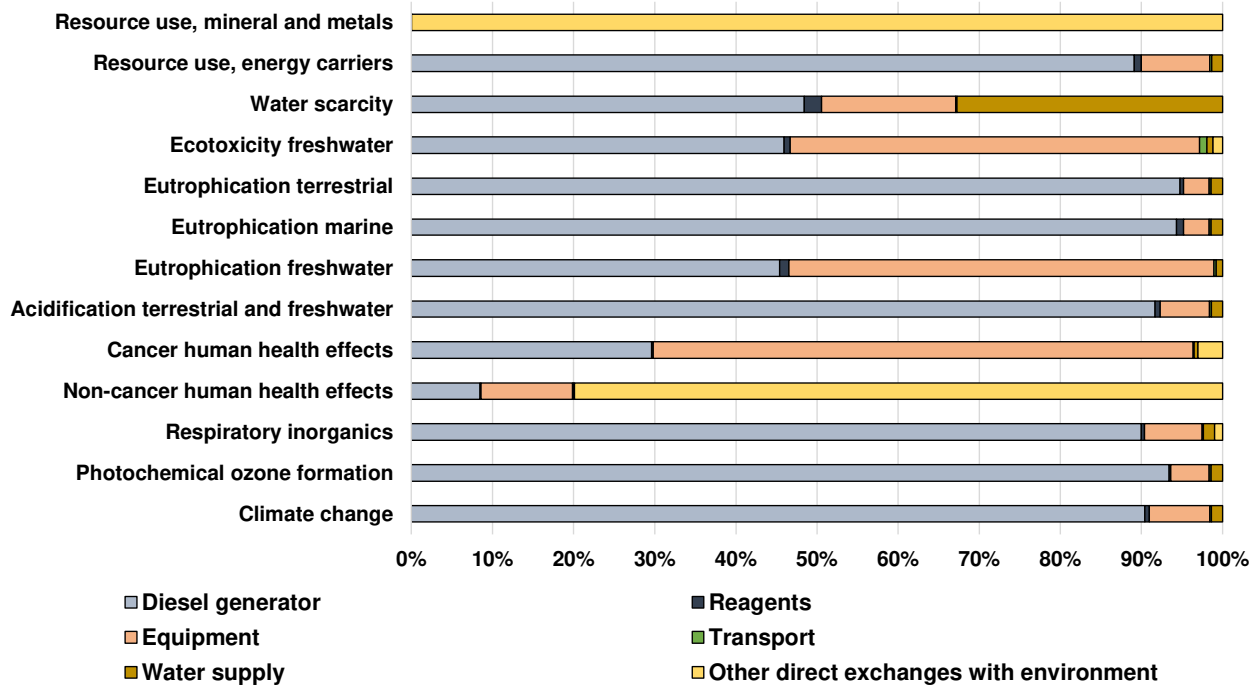
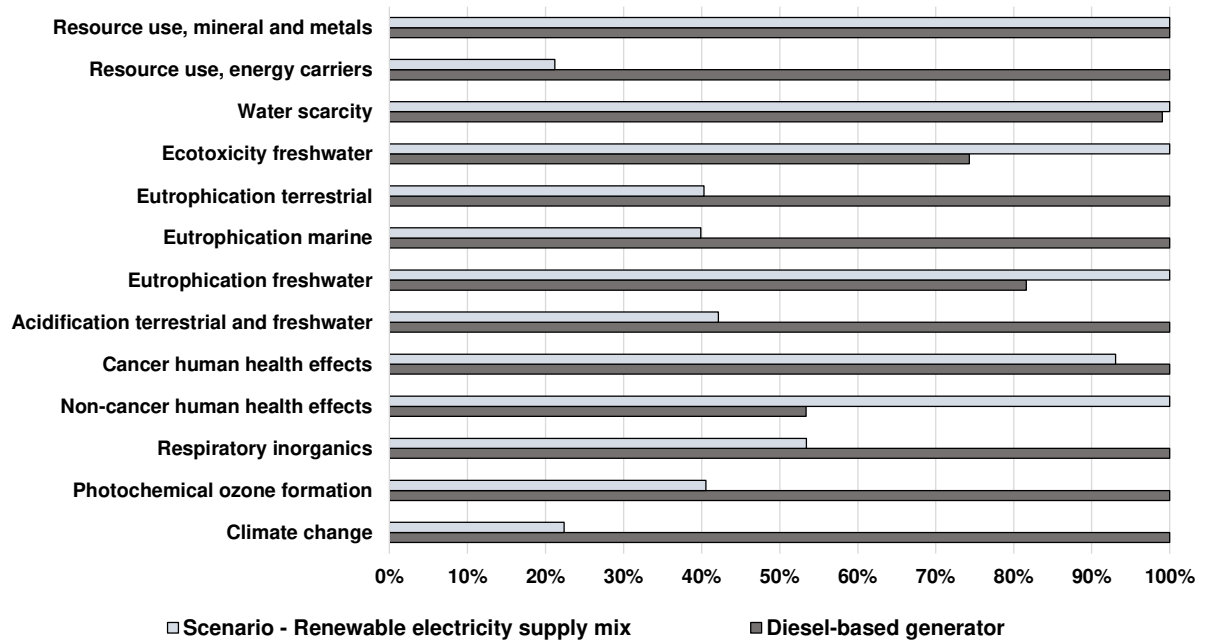


Figure 3: Life cycle environmental impacts induced by the production of one tonne of Pb concentrate at the Olovo site: contributions by exchange with the technosphere and the environment



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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