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Raw materials supply: Kaolin and quartz from ore deposits and recycling activities. The example of the Monte Bracco area (Piedmont, Northern Italy)

Giovanna Antonella Dino [a], Alessandro Cavallo [b,*], Alessandra Faraudello [c], Rossi Piercarlo [d], Susanna Mancini [a]

[a] University of Torino, Department of Earth Sciences, Torino, Italy
[b] University of Milano-Bicocca, Department of Earth and Environmental Sciences - DISAT, Milano, Italy
[c] University of Eastern Piedmont, Department of Business and Economic Studies - DISEI, Novara, Italy
[d] University of Torino, Department of Management, Torino, Italy

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ABSTRACT

Demand and availability of raw materials, especially "critical" raw materials (e.g., rare earths), are becoming increasingly topical issues. In this article we show the potential of an Italian mining and quarrying site (Monte Bracco area, quartzites and kaolin): the combined study of geological, environmental, technical, and economic factors can lead to a sustainable exploitation of the waste from past mining activities, as well as to a resumption of extractive activity of dimension stones and industrial minerals (quartzites, silica and kaolin). The high rare earths contents (especially Y) in the kaolinitic clays also make the site attractive in the critical raw materials arena in a future perspective.

1. Introduction

Raw materials (RM) and critical raw materials (CRMs) supply is a matter of concern and a global challenge to face in a sustainable way (considering economic, environmental, health and social impacts on the society; Ali et al., 2017; Kinnunen et al., 2019). The group of minerals and elements essential for the green-tech transition is quite large: the European Commission estimates that almost 60% of global demand for CRMs is associated with high value-added industries (Moss et al., 2013; EU, 2018). A 2017 World Bank report, on the other hand, found that green technologies "actually have a more material-intensive component than current fossil fuel-based energy systems". With the prospect of limiting the rise in global temperatures by 2 °C by 2050, the UN Environment Program (UNEP) estimates that deploying renewable technologies will require extracting more than 600 Mt of rare metals (Arrobas et al., 2017).

RM/CRMs can be exploited from ore deposits and be recovered from landfills (both urban and industrial), extractive waste (EW) facilities (Extractive Waste Directive 2006/21/EC), and/or from waste streams (urban, industrial, and EW). The focus of the present paper is on the industrial minerals, whose global production reaches nearly 881.3 Mt, equivalent to 108,944 million US dollars (World Mining Data, 2018), and in particular on silica ad kaolinitic clays.

1.1. *Silica and kaolinitic clays: characteristics, uses, productions and potential substitutions*

Silica (SiO_2, the most common polymorph is quartz) mainly derives from sedimentary deposits (quarzitic sands and quartz arenites) and metamorphic rocks (quartzites), sometimes also from acid magmatic rocks (granites, aplites, pegmatites). Ore deposits of silica sand and quartzite are recognizable all over the word, in rocks of every geological age, but the deposits suitable for exploitation are concentrated in some areas. Although most industrial sand deposits contain a high percentage of quartz (≥95%), using RM with lower quartz content is becoming more common as demand for industrial sand outpaces production in certain markets. Quartz is the principal glass-forming compound in a glass batch, as well as an essential ingredient for silicate ceramics, silica refractories, abrasives, proppant sand, filtration sand and building materials (Pohl, 2001; Herron, 2006). Very high-quality quartz crystals are

* Corresponding author.
E-mail addresses: giovanna.dino@unito.it (G.A. Dino), alessandro.cavallo@unimib.it (A. Cavallo), alessandra.faraudello@uniupo.it (A. Faraudello), piercarlo.rossi@unito.it (R. Piercarlo), susanna.mancini@unito.it (S. Mancini).

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used in the optical industry, for prisms and lenses, and in electronics (piezoelectric properties), even in jewelry. Depending on industrial use, different degrees of chemical and mineralogical purity are required (Herron, 2006): the glass (SiO_2 min 98.5–99%, Fe_2O_3 <0.04%, Al_2O_3 0.2–1.6%) and ceramic industries (SiO_2 > 97.5%, $Fe_2O_3 \leq 0.2\%$, $Al_2O_3 < 0.55\%$) are the most demanding, followed by metallurgy (SiO_2 90–95%) and refractories (SiO_2 95–99%). The main producers worldwide are China, Russia, U.S.A., Brazil, South Africa, Ukraine, and France.

Kaolinitic clays are mainly composed of the kaolinite group dioctahedral 1:1 phyllosilicates $Al_4[(OH)_8Si_4O_{10}]$, with minor amounts of other clay minerals (e.g., illite) and impurities (quartz, feldspars). They may occur as primary or secondary deposits (Murray, 2006; Pruett and Pickering, 2006), where the primary type is originated by alteration of feldspars of igneous (granites or rhyolites) or metamorphic rocks (gneisses), due to hydrothermal alteration and/or weathering ("kaolinization"). The secondary type is linked to sedimentary deposits and formed through erosion, transportation, and deposition of mineral particles, typically in continental lakes, rivers and deltas. Kaolin is a global industrial mineral (Pruett and Pickering, 2006) primarily used as a ceramic raw material (kaolinite 75–85%; Fe_2O_3 and $TiO_2 < 0.9\%$), a pigment for paper and paint (kaolinite 90–100%; $0.5 < Fe_2O_3 < 1.85$; $0.4 < TiO_2 < 1.6\%$; virtually no quartz), a functional filler for rubber and plastic (kaolinite >90%; Fe_2O_3 and $TiO_2 < 1\%$), and a component for refractory, brick, and fiberglass products ($35 < Al_2O_3 < 45\%$; $45 < SiO_2 < 55\%$; low alkalis and Fe_2O_3). Kaolinitic clays, especially in weathered-crust elution-deposits, may also host rare earth elements (REE), for example in China (the so-called regolith-hosted ion-adsorption deposits, Jangxi, Fujian, Hunan, Guandong, and Guanxi provinces); there are two types of deposits: light REE (LREE) type, and heavy REE (HREE) type, (Goodenough et al., 2016; Borts et al., 2020, and references therein). These REE deposits (generally low grade, typically 0.05–0.5% rare earth oxides - REO) are considered to have formed by weathering of granitoid rocks, and REEs are in the form of positive hydrated ions, adsorbed on the surface of clay minerals like kaolinite, halloysite and illite.

Main applications of silica and kaolinitic clays (Fig. 1) are listed below:

- Silica (Kogel et al., 2006; Liang et al., 2016; EC, 2017; Flanagan, 2019; EC, 2020.a): glass production (flat, hollow, fiberglass and technical glassware); foundry and metallurgy (casting molds for both ferrous and non-ferrous metallurgy); construction sector and soil (high-end concrete, mortar, glues, grouts, etc. as well as composite silica-resin kitchen-tops, equestrian surfaces, sport soils, silica gravel and traction sand); extraction of crude petroleum (proppant for hydraulic fracturing and well packing/cementing); other uses (filler in plastics, polymers and rubber; extender in paints and adhesives; silicate and carbides for ceramics, abrasives and refractories; filtration sands; chemicals; fluidized bed incinerator plants).
- Kaolinitic clays (Murray, 2006; Pruett and Pickering, 2006; Dondi et al., 2014; EC, 2017; EC, 2020.a): ceramics and refractory industry (floor tiles and sanitaryware, as well as refractories, tableware and glazes. Some kaolinitic clays are employed also for wall tiles and stoneware pipes); filler for paper industries (in bulk paper and to coat its surface); fiberglass and cement (as alumina supplier in the glass and cement batches); catalysts; other uses (as filler and extender in paints, rubber, plastics, cosmetics, and pharmaceuticals).

World production of quartz (including quartzite and other high silica industrial sands) is estimated to be around 315 Mt per year (Brown et al., 2016; Flanagan, 2016; Reichl et al., 2018). The major producers are the US (about 38% of the world total), Turkey (15 Mt), Malaysia (10 Mt), India (8.5 Mt), Brazil (7 Mt), Korea (4.5 Mt), and Australia (3 Mt). The extraction of silica sand in Japan, Mexico, Canada, New Zealand, South Africa, and Iran is between 2 and 3 Mt each. The United Kingdom contributes for 4 Mt per year of silica sand. Silica sand cost was between 30 € and 200 € per ton over the period 2012–2016 (EC, 2017). At EU level high grade silica (>99% SiO_2) is produced in the Netherlands, Italy, France, Germany, Bulgaria, Spain, Poland, Belgium, and the Czech Republic.

Together with ore deposits' exploitation, secondary raw materials (SRM), which can integrate the industrial minerals supply, can be recovered from anthropogenic waste: e.g. recycled glass from urban waste and quartz from quartzite EW facilities. Silica sands for glass production (especially for hi-tech glasses) are not currently substituted but integrated in recycled bottles production: any potential substitute would lead to an increase of cost or a decrease of the benefit/cost ratio, due to a loss of performance. In other sectors, substitution of silica may be envisaged by, e.g., the use of bauxite or kaolin for RM for proppants in the oil field or the use of calcium carbonate, talc, wollastonite, kaolin, mica, pyrophyllite, feldspar as filler materials in several in industrial processes.

Kaolin clays production at global level is constantly increasing, from 38.19 Mt in 2014 to 41.60 Mt in 2018. In 2018, the major producer is China (18%), followed by U.S. (13%), Germany (12%), India (10%), Czech Rep. (9%), Ukraine (%5) and Turkey (4%). Italian production in 2018 was 0.98 Mt (2.3% of the global production) (World Mining Data, 2018). The prices are around 150–200 €/t for kaolin and 50–100 €/t for plastic clays (EUROSTAT, 2018).

Kaolin cannot be recycled from "kaolin containing" products (as it can happen with silica in glass), but several different materials can be used as integrative resources in productive cycles such as (Pruett et al., 2006; Dondi et al., 2014; EC, 2017; West, 2020): pyrophyllite in the ceramic industry; talc, calcium carbonate (ground or precipitated), zeolites, diatomite, or gypsum in the paper production; feldspar in the production of fiberglass; fireclay or pyrophyllite in refractory industry; zeolites, rare earth oxides, silica, alumina, or bauxite as catalysts; calcium carbonate, talc, wollastonite, feldspar, mica, pyrophyllite, silica, diatomite, or bentonite as extender in paints and adhesives; carbonate,

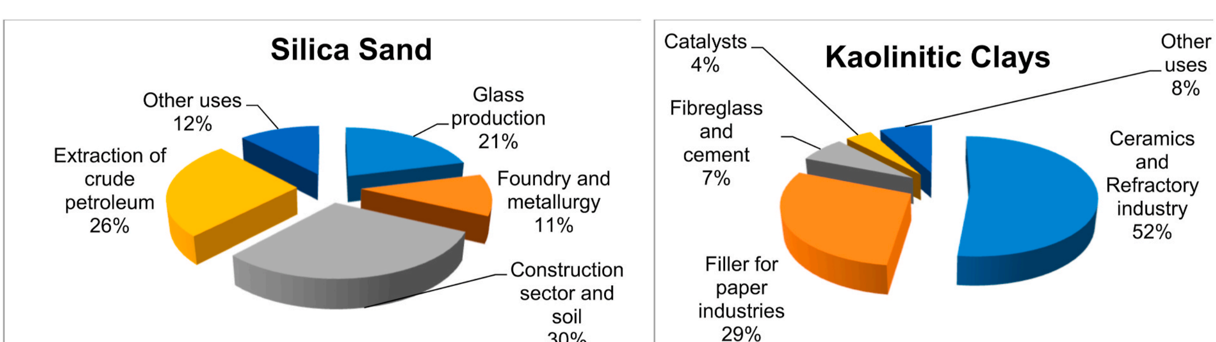

Fig. 1. Main applications of silica (on the left) and kaolinitic clays (on the right). Statistical data for global use, on average 2012–2016.

talc, wollastonite, feldspar, mica, pyrophyllite, silica, diatomite, or bentonite in rubber and plastic industry; and alumina or bauxite in cement industry.

1.2. Outputs of the research

As introduced, the exploitation of RM and CRMs can interest EW facilities (Jones et al., 2013); indeed, huge amounts of RM/CRMs not exploited (because of technologies and methodologies used during the exploitation phase) or not known (e.g., CRMs associated with RM which were not used/known) can be found in old deposition areas (Dino et al., 2018.a). Furthermore, it is mandatory, during the design stage, to evaluate suitable and modern exploitation techniques and dressing activities, to estimate the potential CRMs/SRM associated to the RM principally exploited (volumes, characteristics, market analysis) and the potential impacts associated to the exploitation of RM (CRMs/SRM). Finally, an integrated approach (Pactwa et al., 2018) which include not only the exploitation of the ore deposits but also the mining of past EW facilities (if present) is needed.

The present research investigates the chance to approach in an interdisciplinary way RM/CRMs supply both from ore deposits and EW facilities: technical, economic, environmental, and legal factors connected to the integrated exploitation (ore deposits together with EW) will be introduced. Furthermore, the paper highlights some good practices and suggestions to rethink about the enhancing of local medium-small mining activities, thanks to a sustainable mining approach which includes, together with ore deposit exploitation, the contemporary use of all the extracted materials (SRM, by products) and the exploitation of past EW facilities (if present). This approach is validated thanks to the Monte Bracco (Northern Italy) case study, where three different "ore deposits" (two natural and an anthropogenic one) are present. Some interesting perspectives about the chance to find CRMs (REE in kaolinized gneiss) associated to RM will be introduced.

2. Materials and methods

The goal of this research is the sustainable and integrated exploitation of natural resources and EW: a case study from Monte Bracco area (NW Piedmont – Italy) will be analyzed.

2.1. Integrated approach to RM/CRMs/SRM sustainable supply

When approaching the exploitation of natural resources (RM, CRMs from mining and quarrying activities) and/or alternative resources (such as recycled products, by-products, SRM) different factors must be approached in an interdisciplinary manner (Fig. 2); these factors are:

- Technical factors (2.1.1): exploitation technologies and techniques, logistics, waste management/recovery, environmental rehabilitation.
- Environmental and human health factors (2.1.2): impacts (on soil, water, and air), bioavailability and bio-accessibility of the pollutants, safety conditions.
- Economic factors (2.1.3): costs/revenues connected to operations phases, waste management/recycling, RM/CRMs market, etc.
- Social and legislative factors (2.1.4): EU directives VS local legislation, citizen feelings, governance priorities, local and national policy.

2.1.1. Technical factors

The technical factors are mainly linked to three different phases: ore deposits investigation (1), planning and design stage (2), exploitation phase (3).

Phase 1: ore deposit investigation, which must be carried out including activities such as: field surveys, sampling activity, physical-chemical-mineralogical characterization of the investigated material (s), volume estimation (both for natural and anthropic ore deposits, Dino et al., 2018.a). The data arising from this phase are fundamental to design (Phase 2) the exploitation techniques (Phase 3).

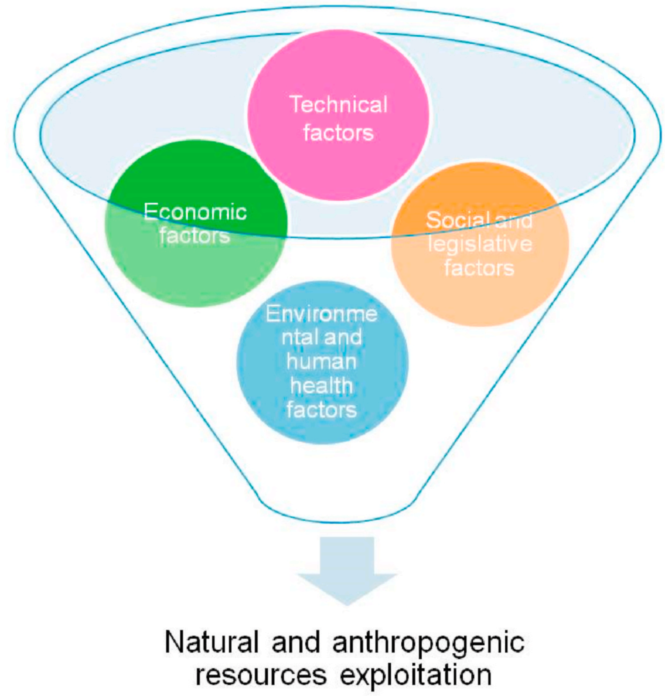

Fig. 2. scheme of the issues to considering when approaching RM (CRMs/SRM) supply in a sustainable way.

Phase 2: planning and design stage, which include the analysis of the data arising from Phase 1 integrated with the study of the existent legislation (legal factors; 2.1.d) connected to exploitation activities (e.g., legislation on mining activities, waste management, potential restrictions, local guidelines for mining activities and/or for use of SRM for public works) and with environmental, economic and social factors (2.1. b, c, d). It has to be highlighted that EW facilities are often rich of RM, not exploited in the past, because the yield of mineral was too low to be exploitable without modern technologies, and of CRMs, not known, nor used (e.g. REE). Thus, EW exploitation is one of the possibilities to exploit RM and CRMs from integrative sources.

The integrated analysis of the data connected to Phase 1 and economic, environmental, social and legal factors will be used to project the mining activities; in particular it deals with:

- mining techniques: open or underground pit, use of machineries and/or explosives, logistics, etc. (Hartman and Mutmansky, 2002);
- mineral processing: flow chart of the processing plant, technologies, logistics, etc. (Navidi Kashani et al., 2008; Hennebel et al., 2015; Wills and Finch, 2015; Gupta and Yan, 2016);
- waste management (MWEI BREF, 2018): study of the potential SRM to recover from mining exploitation and potential by-products from processing phase (Fig. 3, Mathieux et al., 2017; Blengini et al., 2019), chance to recover RM/CRMs/SRM from past EW facilities present in the mining area (Fig. 4, Burlakovs et al., 2018; Afum et al., 2019; Blengini et al., 2019). Even if EW facilities cannot be considered as Landfill (Extractive Waste Directive 2006/21/EC), the approach applied for RM/CRMs/SRM recovery from EW facilities can be intended as landfill mining and enhanced landfill mining approach (LFM and ELFM, Dino et al., 2018.a). Together with the investigation about best techniques and the potential revenue, fundamental is the investigation of potential safety and stability issues associated to waste management (e.g. physical and chemical concerns, such as

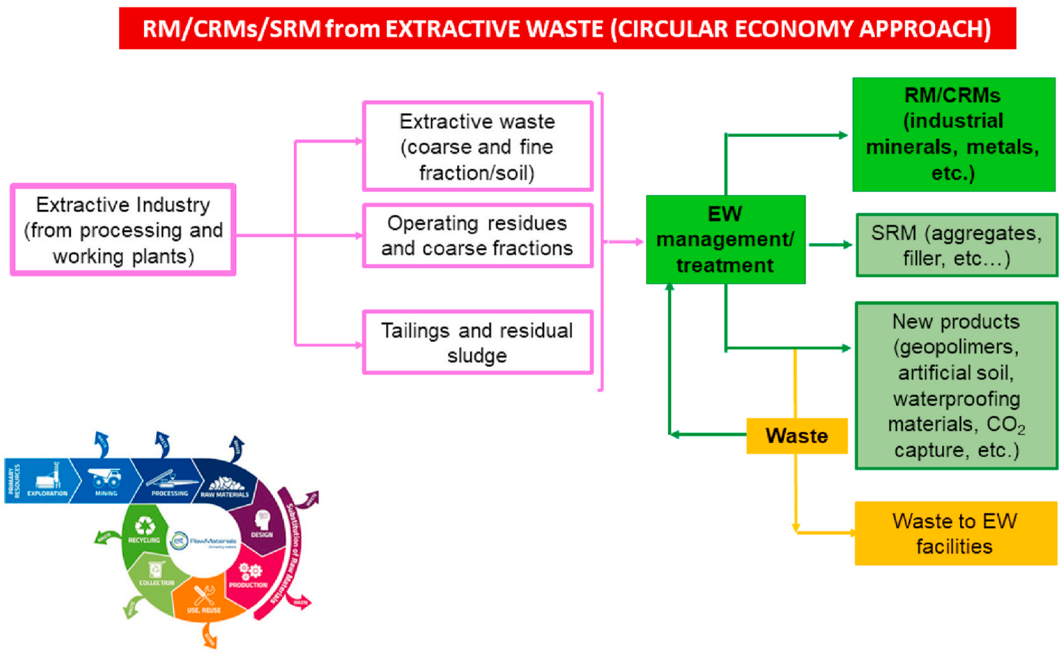

Fig. 3. RM/CRMs/SRM from EW (ongoing activities), in a circular economy approach.

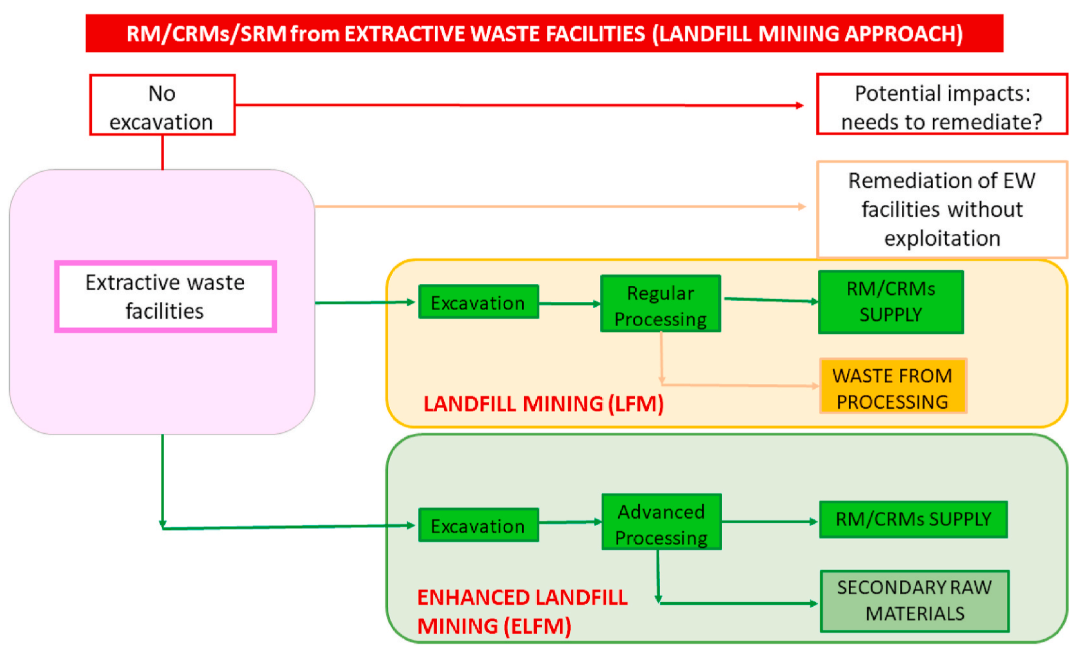

Fig. 4. RM/CRMs/SRM from EW facilities, in a landfill mining approach.

acid mine drainage (AMD) or migration of pollution from EW facilities in case of their exploitation; short term and long term structural stability of the EW facilities, including tailings ponds), together with environmental impacts associated to air, soil and water matrixes (e.g. particles, dissolved substances, dangerous substances and chemical residues, gas and volatile compounds. And also, odor and noise, visual impact and land use, usage of water and consumption of reagents, auxiliary materials, feedstock and energy, Naturally Occurring Radioactive Materials (NORMs), biodiversity, vibrations and induced seismicity). Those studies must be included in the original design stage in order to boost the potential recovery of RM/CRMs/SRM and by-products from the different exploitation phases;

- safety conditions: a detailed analysis of the risks for workers associated to mineral exploitation and to waste management is needed. This analysis will lead to the definition of the procedure to apply in Phase 3 and of the PPE (personal protective equipment) to adopt for workers.

Phase 3: exploitation phase, mining, mineral processing, waste management and safety conditions, which deals with the realization of activities, machineries, and logistics, investigated in the phase 2. Phases 2 and 3 are strictly connected to environmental, economic, and social factors.

2.1.2. Environmental and human health factors

The EWD (Extractive Waste Directive 2006/21/EC), provides measures, procedures, and guidance to prevent and reduce as far as possible any adverse effects on the environment and human health resulting from the management of the EW. In general, the potential negative impacts of mining and processing activities are related to the release of contaminants detectable in the environmental matrices, identified as soil, water and air (Karaca et al., 2018), with detrimental effects on biodiversity and human health, to the consumption of energy, water and soil, to noise (due to machinery and logistics) and to release of hazardous substances.

The main environmental and health impacts associated with mining activities are related to the potential emissions during the rock excavation phases, the management of tailings and waste rocks facilities and, in general, or in the after-care phase of mining activities. These impacts are strictly connected to site characteristics and ore deposit typology (Banks et al., 1997; Gray, 1997; Plante et al., 2015; Béjaoui et al., 2016), climatic conditions and exposure factors depending on land use and the type of receptors present nearby and in the area. Finally, also bursts or collapses of tailings management and waste rock facilities can cause severe environmental damage and problems connected to health safety.

Numerous studies investigated the environmental impacts connected to mining industry and to EW facilities management (Helios Rybicka, 1996; Fields, 2003; Wong, 2003; Azam et al., 2007; Schaider et al., 2007; Tiruta-Barna et al., 2007; González-Corrochano et al., 2014). Tailings, which are conventionally stored in tailing dams, have often caused damage to nearby soils, agricultural land, natural reserves and aquatic life due to dam failure in places like China, Bolivia and Spain (Grimalt et al., 1999; Hudson-Edwards et al., 2001; Liu et al., 2005; Lim et al., 2009; Talavera Mendoza et al., 2016. Health issues can be evaluated thanks to new investigation techniques such as bioavailability and bioaccessibility of pollutants present in waste produced during exploitation phase (Mehta et al., 2020) and based on risk analysis for workers. For a sustainable management of EW, the health-environmental risk analysis could be a valid tool to quantitatively assess the risks for human health related to the presence of pollutants in environmental matrices.

In all cases, for an assessment of all potential environmental and human health impacts related to the different phases of mining activities, a conceptual model is needed. The site-specific environmental and human health risk analysis is based on a general conceptual model (Fig. 5), determined by the identification of: the environmental matrix in which the presence of contamination was detected, the transport mechanism, the potential exposure ways, and the receptors (human or environmental) present at the investigated site (APAT, 2008).

Site investigation, sampling and analysis are essential to provide real data for site-specific conceptual models and subsequently for risk analysis (Pepper et al., 2014; Dino et al., 2018.b).

The permissible limits for the risk calculations can be taken from the specific national legislation and risk analysis guidelines (e.g., as for Italy: Ministero dell'Ambiente e della Tutela del Territorio D.L. 152 del 2006, APAT, 2008). Risk assessment includes not only the identification of the "risk sources" but also the evaluation of the probabilities of actual failure, as well as the severity of the likely consequences to follow from such a failure. In particular, risk analysis can be applied to different scenarios (Figs. 3 and 4): (1) the environmental and human health risks related to mining sites (including EW facilities) if we decide not to exploit them, (2) the environmental and human health risks related to mining sites and EW facilities, in case it is decided to exploit them, (3) the environmental and human health risks if it is decided to move the EW to another place, (4) the environmental and human health risks connected to the different steps of EW treatment.

Environmental factors are closely linked to economic factors both in case of exploitation activities connected to natural ore bodies and from EW facilities (see 2.1.c; Danthurebandara et al., 2017).

According to Stucki et al. (2021), politicians, activists, and researchers are striving towards a more sustainable economy: a brand-new comprehensive way to analyze the environmental sustainability of systems is needed; these new methods should be based on life cycle assessment (LCA). LCA is another internationally standardized approach (ISO 14040) for assessing resource use and related emissions in the supply of goods and services related to the resources. It is bases on impact indicators that are broadly classified into areas of protection, such as ecosystems, health, and resources (Lave et al., 1995; Mancini et al., 2015). LCA should be considered as a method for estimating the environmental impacts of anthropogenic systems, such as products, companies and nations, from a 'cradle-to-grave' perspective (Bjørn et al., 2020). "LCA is particularly relevant from a sustainability perspective, because it covers the entire life cycle of a product or service, avoiding that local improvements only result in shifting the environmental impact elsewhere. LCA differs from other environmental methods by linking environmental performance to functionality, quantifying the pollutant emissions and the use of raw materials based on the function of the product or system" (Jolliet et al., 2015).

2.1.3. Economic factors

There are several economic factors affecting the security of supply of RM. A first group of factors is determined by the micro-dimension of the supply chain: managerial analysis could be useful to detect and report on the use of CRMs to improve efficiency in their use, facilitate their proper life cycle, accelerate their replacement and provide policymakers with adequate information (Ballou et al., 2000; Ballou, 2007). Another group of factors is linked to macro dimension of the international trade system: impact assessment is fundamental to detect all socio-economic and geopolitical issues regarding raw materials, including concentration of supply producers, governance of supply trade, the international market of competitors and substitutability of materials (Schandl and Eisenmenger, 2006; Weisz and Duchin, 2006; Fliess and Mård, 2012). Moreover, innovation in technology exploitation, in logistics deployment and in the novel ways to get the final products may also affect price and availability of some raw materials and eventually the security of supply (Bergek et al., 2008).

The way in which companies build their products and how they affect the social and socio-economic aspects can be evaluated with the social life cycle assessment (S-LCA). This is an emerging tool for assessing the social impacts of products (Arcese G. et al., 2016; Norris, 2006). No standard or code of practice exists, but only guidelines for assessing social aspects of products and their life cycle impact (UNEP/SETAC 2009). In these guidelines, S-LCA is defined as "a social impact (and potential impact) assessment technique that aims to assess the social and socio-economic aspects of products and their potential positive and negative impacts along their life cycle encompassing extraction and processing of raw materials, manufacturing, distribution, use, re-use, maintenance, recycling, and final disposal" (Arcese et al., 2016). Moving the focus to a more economic point of view, the LCA process has been often integrated by the study of economics aspects of every stage of the life cycle of a product. In this sense the LCA and life cycle cost (LCC, Brown, 1979) provide consistent information on the environmental and economic dimensions of sustainability, as they can serve as a basis for the adoption of economically feasible and environmentally sound strategies (França et al., 2021), and it is useful as information in strategic business and policy decision-making (UNEP/SETAC 2009). Guidelines for LCC can be found according to ISO 15686–5 (ISO 2017). As stated in its definition, LCC aims not only to calculate the costs of acquiring RM, but also the costs of operation, maintenance, and final disposal (França et al., 2021), also including a comparison between different alternatives). Thus, the economic indicators can be improved by the decision makers (Shams Fallah et al., 2012). According to Blanchard and Fabrycky (1998), the LCC refers to all costs associated with the system for a given life cycle. When we refer to "all costs" we must consider also the cost related to the phase of the use of the product and all other stages of the life cycle. In this sense, for the total cost of production, the producer must include the costs of the studies behind the possibility to produce something like the R&D costs,

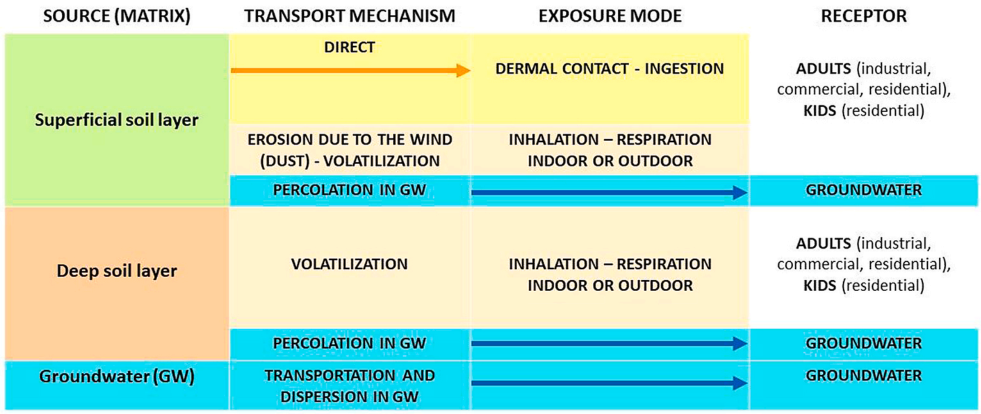

Fig. 5. General conceptual model of specific site environmental and human health risk analysis.

as well as all the manufacturing resources necessary. All these costs are usually included in the selling price, so it could be easier to estimate their weight, but, in addition, it could be necessary to think about the costs related to the use of a product, like electricity and similar (Jolliet et al., 2015).

The economic investigation for the investigated case study has been carried out on a quarrying area that is not operational and is not expected to be reactivated soon; for these reasons a Cost Benefit Analysis (CBA) evaluation has been preferred. CBA is a method for estimation which allows processes to be evaluated on a comparison between their costs and benefits (Snell, 2011; OECD, 2018). As to RM, CBA is mainly dedicated to identifying:

- the relevance of the use of SRM to assess whether the effects of the environmental impacts are greater than the benefit for the society at large;
- the criticality of RM linked to the probability of a supply disruption of a material and the risks deriving from this disruption for national systems, industrial sectors, or a single company.

Normally the CBA includes a qualitative analysis consisting in the assessment of the benefits and a quantitative analysis which compares different costs (extraction cost, construction cost, technology cost, operating costs etc.) to determine the lower costs. The main problem with CBA is to ascertain the proper ratio between the value of the total costs and the benefits are qualitatively selected and, especially in the case of raw materials, they essentially concern different types depending on whether the timeline is over the short, medium or long term and whether microeconomic or macroeconomic aspects are involved.

A variety of market analysis methods have been developed in recent years. An analysis focused on RM management scenarios is therefore useful and necessary, both for the production of materials, appliances and infrastructure required by the energy transition, and as risk components of energy management, constituting a potential obstacle to technological innovation. Induced by the pandemic to reconsider some risk mitigation strategies, diversification and resilience along global value chains have become key words for policymakers and entrepreneurs. In this context, which has ended up further exacerbating friction between the US and China in technological competition, a new, potentially conflictual scenario is emerging: the race for CRMs and minerals. This is a process of uncertain governance, which the disruptive impact of new digital technologies and the use of renewables to de-carbonize the world economy will make difficult to avoid (Kalantzakos, 2020). Given the rapidly changing geopolitical context, there is a growing opinion that it will be difficult for the free market alone to mitigate the simultaneous overlap of two global trends and drivers of renewed competition for CRMs: energy conversion and the advent of the fourth industrial revolution. While some of the literature argues that these phenomena, with the progressive integration of AI, IoT and the energy basket, may represent the premises for a new stage of growth and development, distorting effects cannot be ruled out, since the two phenomena are increasingly part of a logic of great-power competition for technological and industrial supremacy, whose foundations are increasingly embedded in the CRMs supply.

2.1.4. Social and legislative factors

To facilitate the sustainable supply of RM/CRMs from European deposits, the European Commission aims to secure the right legal and regulatory conditions. The European Commission proposed targeted measures to promote investment in extractive industries in Europe by the means of some policy initiatives. The first one is consisting of an exchange of best practices through ad-hoc expert group in land use planning and administrative conditions for exploration and extraction (EC, 2011.a). The second one is the adoption of guidelines on extraction to reconcile extractive activities with the compliance of Natura 2000 areas with biodiversity protection (EC, 2011.b). Another initiative is related to the development of indicators showing how the legislation impacts on the performance of the extractive sector (EC, 2014). Finally, specific policy instruments have been set about CRMs with the adoption of the List of CRMs, which has been published every three years since 2011 (last update in 2020, in accordance with an Action Plan to ensure European security of supply by diversifying suppliers, investing in domestic sourcing, and promoting circularity to achieve secondary supplies. EC, 2020.b); as well as the European Innovation Partnership (EIP) on RM, that is a stakeholder collaboration platform encouraging and promoting innovative solutions for ensuring sustainable and secure supply of CRMs.

As to SRMs, EU has produced laws on the disposal of waste and laws concerning the environmental performance of products for over 20 years. However, this legislative production is not forming a cohesive whole, but sectoral legislation has been enacted, such as Ecodesign Directive (Directive, 2009/125/EC), Energy Labelling Regulation (Directive, 2017/1369), Ecolabel Regulation (Directive 66/2010), Green Public Procurement Directive (Directive, 2014/24/EU), Directive 2018/851/EU on Waste Responsibility, Waste Framework (Directive 2008/98/EC), Directive 94/62/EC on packaging and packaging waste. The EC also published the policy document about the Circular Economy Package that calls for further clarification of the definition of waste, as well as for a better application of the waste hierarchy with emphasis being put on increasing both the quantity and the quality of recycling (EC, 2015).

According to the United Nations (Sustainable development goals[1]),

[1] United Nation—Sustained Development. Available online: https://sustainabledevelopment.un.org/topics/mining (accessed on July 2021).

suggestions to maximize the development benefits of mining while improving the environmental and social sustainability of the mining sector were first addressed in the Johannesburg Plan of Implementation (JPOI), where environmental, economic, health and social impacts and benefits of mining throughout their life cycle were identified as priority areas.

The need to minimize waste generation, to reduce its impacts on the environment and to conserve natural resources, and, at the same time, create the opportunity for the reuse/recycling of waste materials, is in line with the EU policy expressed in the Europe 2020 strategy for smart, sustainable, and inclusive growth (EC, 2020.c) in the EU Sustainable Development Strategy (EC, 2001, 2005) and the Paris Agreement document (UNFCCC, 2015). Indeed, to strive for sustainable and efficient management and recovery of the extractive waste (EW), it is fundamental to guarantee the reduction in the environmental impacts associated with EW management. Moreover, it should be mandatory to ensure market conditions suitable for the new "recycled" products (by-products, secondary raw materials—SRM) coming from EW exploitation, together with higher awareness about the importance and convenience of using recycled products as alternative (integrative) to the ones coming from the exploitation of natural resources. All those principles are in line with the Green Deal road map.

According to this EU framework, present legislation on mining activities and on EW must be faced, together with existent guidelines for EW management and recovery (where present). EU guidelines about EW management aim for the exploitation, based on environmental protection, of materials which can be recovered and recycled, with a consequent natural resource's preservation. Thank to this approach EW would not be considered as waste but as resources (Careddu et al., 2018). All these factors must be considered to decide if and when an ore deposit (including EW facilities, intended as "new ore bodies") can be sustainably and profitably exploited.

A case study (Monte Bracco area, see paragraph 2.2.) can be considered as a paradigm to validate the methodology here introduced; it shows two different typologies of "ore deposits":

1. Natural ore deposits: *Bargiolina* quartzite (ornamental stone) and kaolin clays from kaolinitic gneisses occurring in the area.
2. Anthropic ore deposit: quartz from quarry waste facilities (from quartzite past exploitation, to be intended as a "new ore body").

2.2. Monte Bracco case study

The Monte Bracco area (western Alps, northern Italy) is placed in the Dora Maira Massif, a geological and structural unit belonging to the inner part of the Penninic Domain. Monte Bracco is an isolated relief,

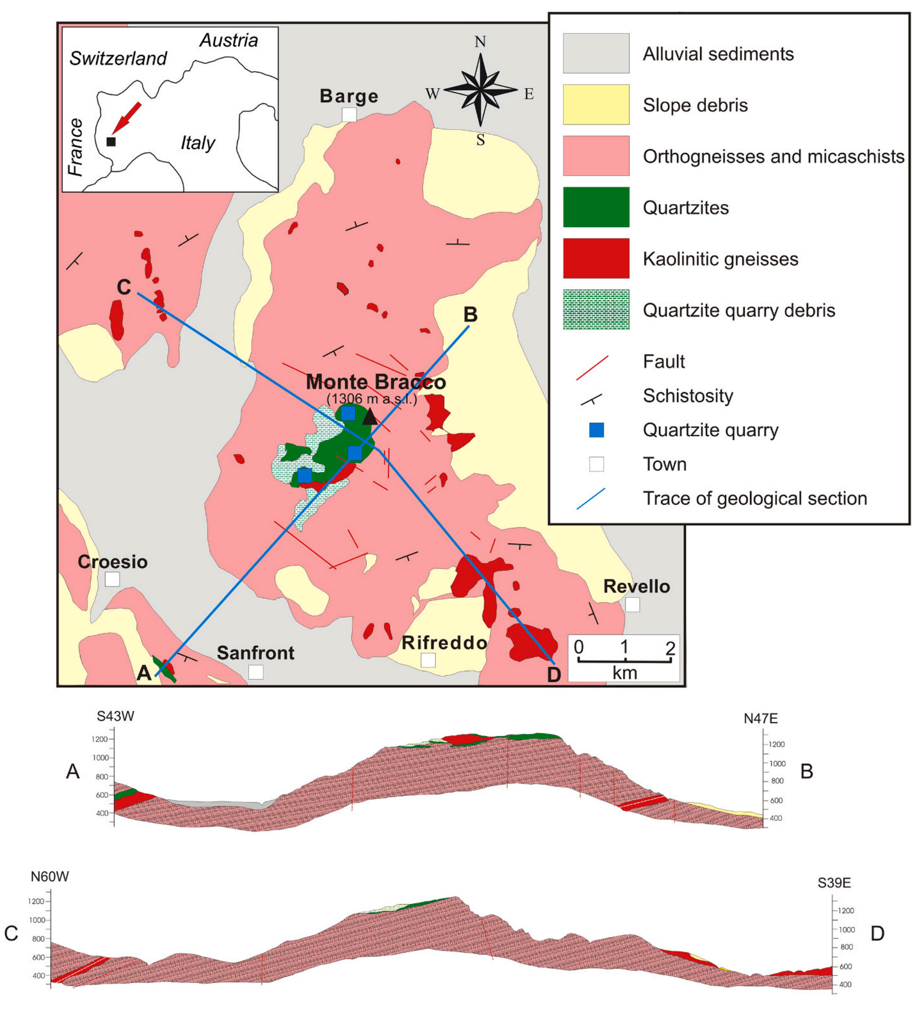

Fig. 6. Simplified geological sketch/map and AB-CD sections of the Monte Bracco area. The quarzitic bodies (in green) occur mainly on the top, whereas kaolinitic gneisses (in red) are widespread over a huge area. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

North-South elongated, mainly formed by phengite-bearing ortho- and paragneisses, and some lenses of quartzites that crop out in the uppermost part of the mount (Compagnoni et al., 2012). The quarzitic bodies (thickness between 2 and 10 m) occur as concordant layers or as asymmetric lenses, both capping the gneisses and intercalated into them (Fig. 6); the quartzite have been quarried by different companies as ornamental stones (*Bargiolina*, Cavallo and Dino, 2020). At the southern top of Monte Bracco (Tre Fontane quarry), a deep clayey alteration ("kaolinization") of the gneisses occurs: the completely altered rock appears brightly white in color, with poor cohesion, but still showing a well preserved "ghost foliation", highlighted by elongated quartz ribbons and by thin black tourmaline layers. At the end of the XX cent. a mining company exploited the kaolinitic gneiss as RM for the ceramic industry. A field prospecting was carried out all around the Monte Bracco area, and, as a result, further different zones were found, where the gneiss shows a widespread and well developed kaolinization. Aerial photography and field surveys, detailed geological mapping and geochemical and mineralogical sampling were performed on them and on the Monte Bracco exploited zone (kaolinitic gneiss, quartzite dimension stone and quartzite waste rocks).

3. Results and discussion

3.1. Technical factors

Following the structure presented in the M&M chapter, it is possible to group the technical factors into 3 different phases. Two of them can be here introduced based on collected data (phase 1) and of planning and design activities (phase 2) to exploit both the exploited ore and the "virgin" bodies (kaolinitic gneiss and quartzite quarry waste). On the other side, the exploitation phase (phase 3) cannot be detailed reported in the paper, because no exploitation activities on quartzite quarry waste nor on the kaolinitic gneiss (especially in the Sanfront, Revello and Rifreddo areas) have been started so far.

3.1.1. Phase 1: ore deposits (and EW facilities) investigation

During the last 20 years, few research investigated the Monte Bracco area; these investigation activities included:

- field survey to collect samples for the characterization of materials (quartzite as ornamental stone, quartzite from EW facilities, kaolinitic gneiss) and to define the exploitable areas and resources volumes,
- RM and extractive waste (EW) characterization (Table 1);
- estimation of EW facilities and kaolinitic gneiss volume.

Thanks to detailed field surveys carried out during two different periods (2000–2004 and 2018–2019; Dino et al., 2001; Cavallo and Dino, 2019) it was possible to produce geological maps and cross sections fundamental to estimate areas and volumes (reported in Table 2) of the three typologies of ore deposits present in the investigated area (*Bargiolina* quartzite, quartzite waste rocks and kaolinitic gneiss, Fig. 4).

Representative samples were collected to characterize the different materials from the Monte Bracco area: Tre Fontane – Pian Martino – Pian Lavarino (on the top of the Monte Bracco), Montescotto, Revello, Rifreddo (Case Chiotte, San Bernardo, Ca Martina localities), Envie.

The collected samples were characterized for mineralogical composition by X-ray powder diffraction (XRPD) and whole-rock geochemistry [major elements by energy-dispersive X-ray fluorescence (EDXRF), REE by inductively coupled plasma mass spectrometry (ICP-MS)]. Particle-size, microstructures and mineral chemistry were assessed by scanning electron microscopy and energy-dispersive spectroscopy (SEM-EDS). XRPD analysis was performed using a Bragg–Brentano θ–θ PANalytical X'Pert PRO PW3040/60 x-ray powder diffractometer, with Ni-filtered Cu Kα radiation at 40 kV and 40 mA, ½° divergence and receiving slits, and step scan of 0.02° 2θ, in the 3–80° 2θ range. The qualitative phase analysis was performed using the PANalytical HighScore Plus software version 2.2c; quantitative phase analysis was carried out running the FULLPAT software (Chipera and Bish, 2002). Bulk geochemistry was assessed for major elements (Panalytical Epsilon 3-XL EDXRF spectrometer), whereas REE by ICP-MS (whole rock fusion with meta-borate), at the Chemistry Labs, Vancouver (Canada). The SEM (Vega TS Tescan 5163 XM) was used in combination with an EDS analyzer (EDAX Genesis 400) with 200 pA and 20 kV, using natural standards for EDS microprobe.

The kaolinitic gneiss contains appreciable amounts of kaolinite (e.g., Fig. 7, up to ≈32% wt.%, range 8–22 wt%), with minor illite (up to 15 wt %), the remaining phases are represented mainly by quartz, plagioclase (albite), phengite and traces of K-feldspar; typical accessory minerals are zircon and apatite. There is an appreciable enrichment in REE, that are preferentially "adsorbed" on clay minerals (especially illite) or occur in phosphates, such as xenotime, relatively abundant due to its resistance to weathering and alteration (Fig. 8). Kaolinite occurs in euhedral, hexagonal, platy crystals, often stacked together as vermicular or book-like aggregates.

The kaolinitic gneiss samples show an appreciable enrichment in Y (Fig. 9), with a total REE content in the 650–1480 ppm range (median 1100 ppm). Of course, this is only a preliminary study, inferred from surface samples: in the vision of a possible exploitation of REE, core drilling surveys and further analytical investigations are required, to assess their distribution and concentration as a function of depth, as well as a correct assessment of ore volumes.

Table 1.a and Table 1.b report the geochemical and mineralogical analyses of the RM samples respectively.

The volumes of reserves concerning *Bargiolina* quartzite (as ornamental stone), quartzite quarry waste (silica for glass and ceramic industry) and kaolinitic gneiss present on the top of the Monte Bracco are reported in Table 2.a). They were calculated based on the visible areas interested by ore deposits (*Bargiolina*, quartzite EW and kaolinitic gneiss) and the estimated thickness (Fig. 4), using the formulas for

Table 1a

Geochemical analysis (major and minor elements, wt.%) of the RM from Monte Bracco area.

SAMPLE	MB1	MB10	MB11	MB9	MB21	MB22	MB23	MB27	MB28	QZ4	QZ5	GN1
	%	%	%	%	%	%	%	%	%	%	%	%
SiO_2	61.99	61.75	59.84	37.17	69.41	60.9	65.55	82.75	71.11	90.81	96.79	69.83
Al_2O_3	25.40	25.98	27.50	46.71	17.37	25.47	22.49	7.02	12.36	5.39	2.12	19.87
Fe_2O_3	1.06	1.10	0.95	0.86	1.19	1.58	0.74	1.5	3.20	0.48	0.31	0.97
Na_2O	0.65	0.60	0.59	1.02	1.21	0.70	1.29	1.13	2.67	0.30	0.06	0.81
K_2O	8.17	7.81	7.83	11.68	8.75	7.95	8.70	4.53	5.08	2.84	0.08	7.71
CaO	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	0.13	<0.03
MgO	0.20	0.28	0.12	0.25	0.18	0.20	0.05	0.35	0.71	0.05	0.35	0.26
L.O.I.	2.50	2.45	3.14	2.28	1.86	3.17	1.15	2.69	4.84	0.1	0.12	0.45

MB1, MB10, MB11: samples from the Tre Fontane mining area (Monte Bracco); MB9: sample of a kaolin vein of the Tre Fontane area; MB21, MB22: samples from Envie area. MB22: reddish vein in an oxidized kaolinitic gneiss; MB23: samples from Rifreddo area (Case Chiotte); M27: sample from Robella area; MB28: sample from Montescotto area; QZ4: foot-wall quartzite; QZ5: quartzite from the top of the Monte Bracco; GN1: unaltered gneiss.

Table 1b
Main rock-forming minerals (by quantitative XRDP, range, wt.%) of the different quartzite varieties and kaolinitic gneiss (* from Cavallo and Dino, 2019) present in the Monte Bracco area. Abbreviations after Whitney and Evans (2010): Qtz = quartz; WM = white mica; Phg = phengite; Kfs = K-feldspar; Pl = plagioclase; Chl = chlorite; Kao = kaolinite; Ill = illite; LOD = limit of detection ≈0.5 wt%).

MINERALS	"GOLDEN" QUARTZITE*	PALE YELLOW QUARTZITE *	OLIVE GREEN QUARTZITE*	MARMORINA QUARTZITE*	MB TRE FONTANE AREA (ON AVERAGE)*	MB10	MB23
	%	%	%	%	%	%	%
Qtz	90–95	85–90	85–90	70–80	50–70	53	55
WM/Phg	2–6	2–8	5–10	10–15	5–15	6	5
Kfs	1–2	1–5	2–5	2–10	<LOD	8	6
Pl	1–2	1–2	2–4	2–4	<LOD	8	12
Chl	<LOD	<LOD	traces	traces	3–8	<LOD	1
Kao	<LOD	<LOD	traces	traces	8–35	21	15
Ill	<LOD	<LOD	<LOD	<LOD	<LOD	4	5
Others	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	1

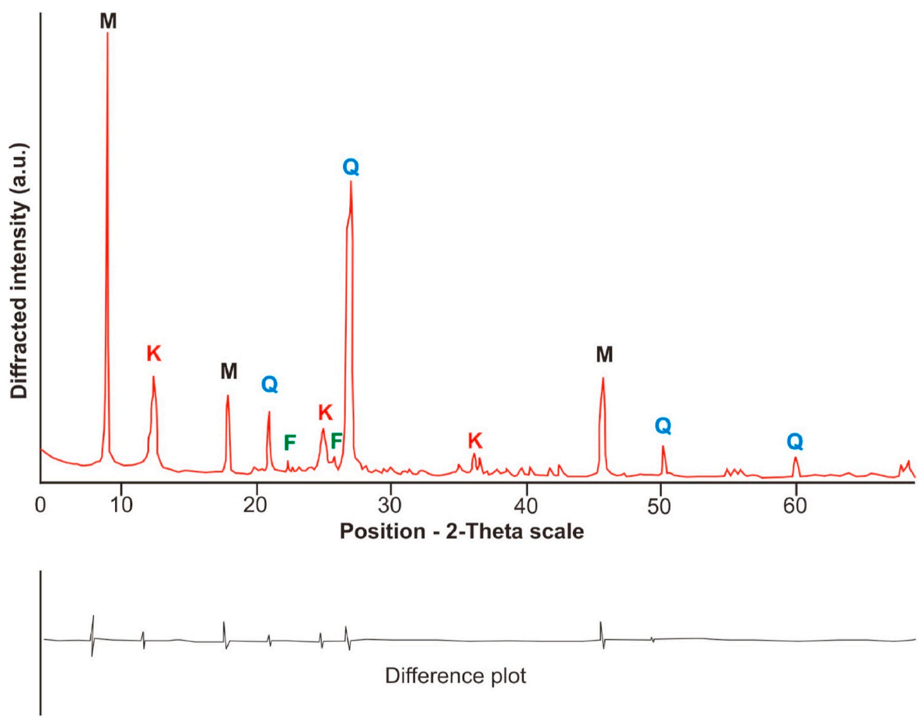

Fig. 7. Representative diffractogram of a typical kaolinitic gneiss sample; M = micas; K = kaolinite; Q = quartz; F = feldspars. The difference plot shows the differences between the measured and calculated pattern (FULLPAT, Chipera and Bish, 2002).

volume calculation applied to geometric solids approximating the shape of each part of the investigated ore bodies.

Indicated resources and inferred resources concerning kaolinitic gneiss and quartzite quarry waste (only the inferred resource) are reported in Table 2.b and 2.c respectively.

In those two cases the volumes were calculated basing on areas and thickness not directly obtained during the field surveys but estimated after the production of specific maps and sections.

3.1.2. Phase 2: planning and design activities

Based on the data and maps collected and produced during the phase 1, and considering that the exploitation of the resources present in the area can be considered as sustainable, thanks to the data (or assumptions) arising from the evaluation of economic, social and environmental impacts (see paragraphs 3.2, 3.3 and 3.5), the steps to follow for the planning activities are:

Step 1. definition of quarrying/mining techniques and technologies to adopt depending on the morphology of the ore deposits and on the knowledge level of the area (top on Monte Bracco, Tre Fontane, Pian Martino and Pian Lavarino areas are well studied). Starting with the three different typologies of ore deposits at the top of Monte Bracco, the following techniques and technologies can be indicated:

- *Bargiolina* quartzite: exploitation of the accessible benches using combined techniques of explosives and pneumatic hammer.
- Quartzite quarry waste*:* exploitation of the EW facilities using excavators.
- Kaolinitic gneiss: exploitation of the benches using dragline and excavator.

As for the other investigated areas, it must be noticed that the more valuable kaolinitic gneiss deposits are the ones in Rifreddo and Sanfront. Theoretically, the exploitation technologies to suggest in those cases are the same suggested for the area on the top of the mount. A deeper investigation phase by core drilling is suggested, to confirm volumes of the estimated indicated and inferred resources.

Step 2. definition of the technologies and flowcharts to adopt for the working (*Bargiolina* quartzite) and dressing (quartzite quarry waste and

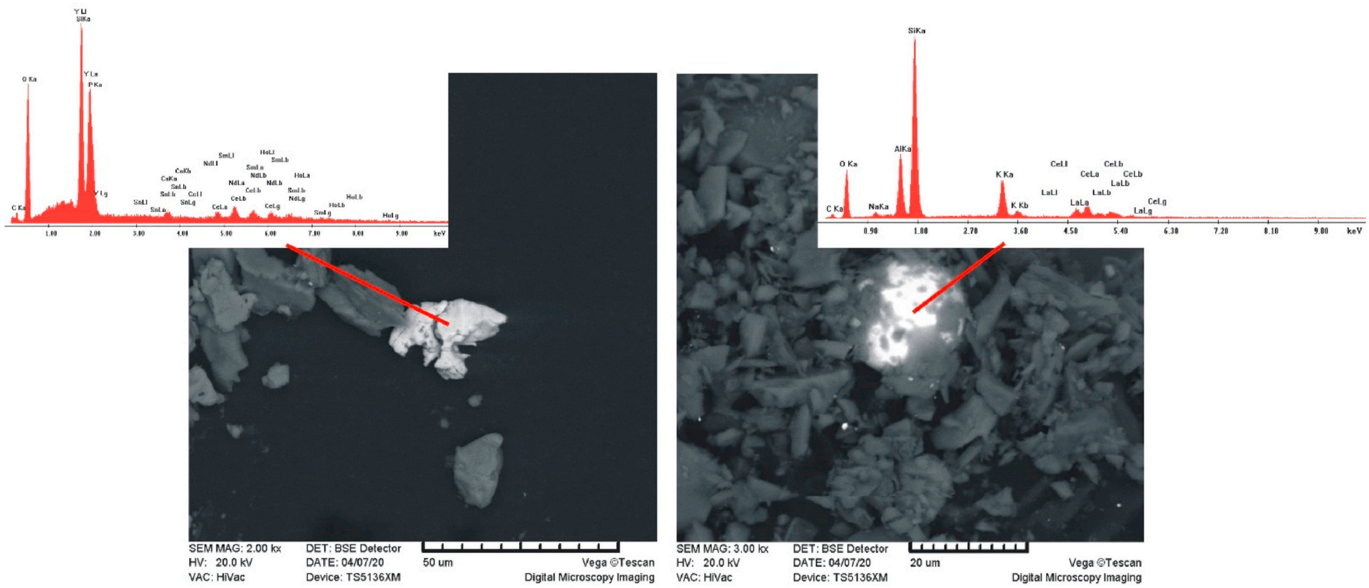

Fig. 8. SEM back-scattered electron micrographs of kaolinitic gneiss samples. A xenotime grain is shown on the left, whereas a LREE-enriched illite grain is evidenced on the right.

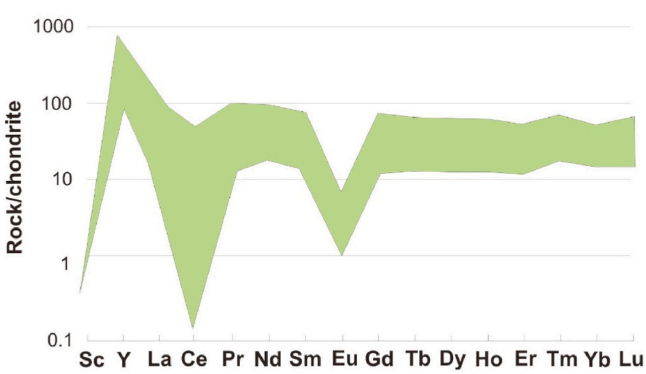

Fig. 9. Rock/chondrite normalized spidergram of the kaolinitic gneiss (mean of 32 samples). Chondritic values after Nakamura (1974) and Wood et al. (1979) (Sc and Y).

Table 2a
Estimation of the reserve of RM exploitable from Monte Bracco (quartzite as ornamental stone, quartzite EW and kaolinitic gneiss).

	QUARTZITE (ORNAMENTAL STONE)	QUARTZITE EW	KAOLINITIC GNEISS (TRE FONTANE AREA)
Total estimated volume (m^3)	3,630,000	2,250,000	3,765,000
Correction factor	0.12–0.2	1	1
Volume of exploitable resource (on average, m^3)	435,600–726,000	2,250,000	3,765,000
Exploitable resource (on average, t)	1,119,500–1,865,800	4,118,080	8,659,500

kaolinitic gneiss) plants.

- *Bargiolina* quartzite: the quarried material which shows the proper characteristics to be used as ornamental stone (about the 20–30% of the quarried materials) must be transported to local working plants to be transformed in slabs, tiles, curbs, cobbles, etc. The EW produced during the quarrying phase are, usually, disposed in EW facilities present on the top of the Monte Bracco, could be treated in a dressing plant (as briefly described in Step 3 and reported in Fig. 10).
- Quartzite EW: based on the Bargiolina geochemical and mineralogical composition (Table 1.b), it could be noticed that the best reuse for the treated quartzite wastes is for glass and ceramic industries. The project planning for the quartzite Bargiolina wastes exploitation is based on the physical-chemical characteristics of the rock and on the quantity of EW useful for the recovery. These parameters heavily influence the treatment plant project: including different kind of crushers, sieves, materials handling equipment (power loaders, diggers), etc. They also influence the choice for mineral wastes concentrating processes, to define the products commercial destination (Step 3, Fig. 10).
- Kaolinitic gneiss once mined must be transported to dedicated treatment plant to obtain RMs for ceramic industry.

Step 3. individuation of the EW management plan (including recovery/recycling), specific for *Bargiolina* and kaolinitic gneiss exploitation (and in case of waste arising from quarry waste exploitation).

The *Bargiolina* wastes volumes evaluation, the geochemical and mineralogical analysis referred, and the know-how acquired during the years let us plan a pilot treatment plant for quartzite EW (Fig. 10). The dressing plant should be placed on Monte Bracco quarry hillside, so that the feeding of the plants, both with current wastes (from Pian Lavarino and Pian Martino quarries) and wastes from ancient dumps, should be assisted.

The waste treatment should contemporarily guarantee the total reuse of the current quarry wastes and of the rock wastes located in not yet rehabilitated dumps. Such a way it should be avoided not only the realization of new dumps, but also it should be reduced the costs for the safety conditions and to the dump's rehabilitation.

STEP 4. individuation of the best safety condition to adopt for the specific case study.

The safety condition to adopt are mainly connected to the slope stability (quartzite quarry dumps) and to the risks connected to quartz dust (diseases related to silica). It is important to design the quartzite waste recovery to avoid the collapse of the dump debris. Furthermore, to avoid diseases connected to silica dust, wetting tools to use on the roads

Table 2b
Evaluation of the indicated resources of kaolinitic gneiss in the Monte Bracco area at large.

	TRE FONTANE	ROBELLA	RIFREDDO (LOC. CA MARTINA)	RIFREDDO (LOC. SAN BERNARDO)	RIFREDDO (LOC. CASE CHIOTTE)	ENVIE
Total estimated volume (m^3)	8,830,000	765,000	740,000	12,630,000	10,260,000	2,140,000
Correction factor	0.7	0.5	0.6	0.6	0.6	0.6
Volume of exploitable resource (on average, m^3)	6,183,100	382,500	444,000	7,578,000	6,156,000	1,284,000
Exploitable resource (on average, t)	14,221,100	879,750	1,021,200	17,429,400	14,158,800	2,953,200

Table 2c
Evaluation of the inferred resources of kaolinitic gneiss and quartzite EW in the Monte Bracco area at large.

	QUARTZITE EW	TRE FONTANE	RIFREDDO (LOC. SAN BERNARDO AND CASE CHIOTTE)	ENVIE
Total estimated volume (m^3)	4,940,000	14,580,000	25,890,000	1,400,000
Correction factor	1	0.4	0.2	0.2
Volume of exploitable resource (on average, m^3)	4,940,000	5,832,000	5,178,000	280,000
Exploitable resource (on average, t)	11,660,000	13,413,600	11,909,400	644,000

and in the quarrying yards must be foreseen.

It is of paramount importance that the companies interested in RM exploitation, mainly in the extractive areas present on the top of Monte Bracco, coordinate to program Step 1, 2, 3 and 4.

3.1.3. Phase 3: exploitation phase

As introduced, at present no extractive activities are present on the Monte Bracco area, except for a very small exploitation of *Bargiolina* in Sanfront and Barge quarry sites. The present research should give some inputs for a sustainable and integrated extractive activity which includes the contemporary exploitation of *Bargiolina* (ornamental stone), quartzite EW facilities and kaolinitic gneiss (industrial minerals). Indeed, as introduced, the exploitation of quartzite needs a contemporary management of kaolinitic ore deposit. Furthermore, EW facilities could represent a risk for slope stability and for environmental impacts connected to silica dust dispersion; at the same time, the EW coming from quartzite exploitation will produce huge quantities of EW (exploitation yield is 20–30% on average) which need to be managed and recovered. Thus, a dressing plant to recover silica sand from EW facilities should be projected (see phase 2) and built.

3.2. Environmental factors

In Italy, the present legislation about EW and EW facilities management is the DLgs117/2008. EW may contain significant amounts of hazardous substances (usually heavy metals); thus, a site-specific risk analysis can be used to assess the state of contamination of environmental matrices, quantifying current and potential risks to humans and

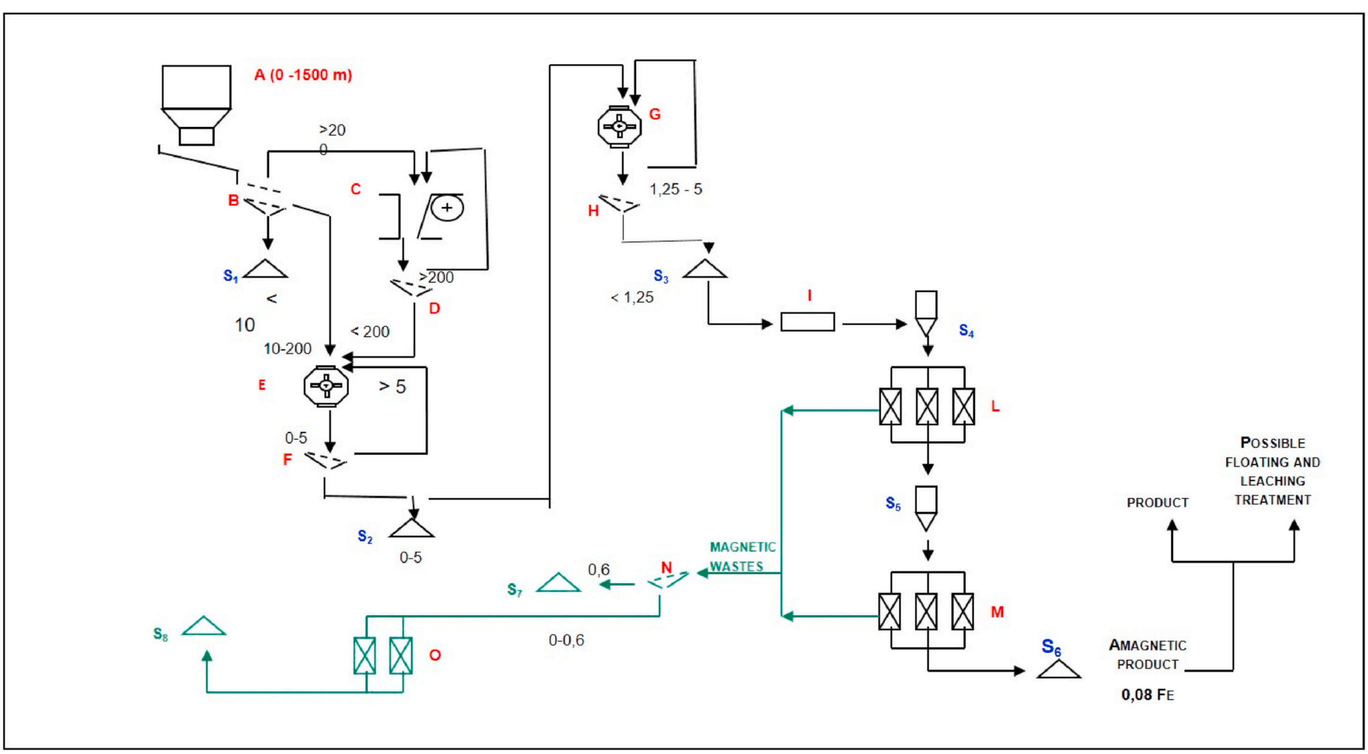

Fig. 10. "Dry process" plant flowsheet for quartzite quarry wastes (in black). It is also shown a possible treatment concentrating phase (in green). Where: A: vibrating feeder; B: vibrating screen classifier (200-10 mm); C: jaw crusher; D: vibrating screen classifier (200 mm); E: gyratory crusher; F: vibrating screen classifier (5 mm); G: gyratory crusher; H: vibrating screen classifier (1.25 mm); I: continuous dryer; L: magnetic separators; M: magnetic separators; N: vibrating screen classifier (0.6 mm); O: magnetic separators. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

the environment.

Often, one of the main problems linked to EW management is connected to the inhalation of airborne dust containing harmful or carcinogenic substances (e.g., silica) generated during the drilling, the cutting, the grinding phases and occasionally during the transit of vehicles (Campopiano et al., 2007). Crystalline silica occurs generally as quartz, a common rock-forming mineral of many magmatic, sedimentary, and metamorphic rocks. The harmful effects of this substance can be due to the inhalation of fine dust; the danger of dust is inversely proportional to its size: as its size decreases, its ability to penetrate the lungs is greater ($d < 4$ μm – conventional curve UNI EN 481). In Italy, D. L. 44/2020 implementing Directive 2017/2398 (EU) was recently issued, in which respirable crystalline silica dust was included in the list of carcinogenic agents, reporting 0.1 mg/m^3 as occupational exposure limit value (VLE occupational update Annex XLIII of D.L. 81/2008).

A specific site risk analysis approach to EW was made by applying the Risk-net software (Metha, 2018).

Risk-net is a software program that allows users to apply the risk analysis procedure to contaminated sites in accordance with the provisions of Risk Based Corrective Action (RBCA) (ASTM, 1995, ASTM, 2015). This method refers to an approach towards managing contaminated sites that examines the risks posed to human health and the environment (groundwater resource) due to contaminants (direct mode) and compute a specific representative concentration (CRS).

As waste management should aim at minimizing the negative consequences of waste generation and management for human health and the environment, the application of a methodology according to the scheme of site-specific environmental and health risk analysis can be useful for a preliminary assessment of potential environmental and health risks arising from exploitation activities. The conceptual site model for the silica dust contamination for the present research is reported in Fig. 11. The contamination source is potentially volatile silica dust with a diameter of less than 10 mm, because it is only the respirable fraction that is carcinogenic. The size of the contamination source area is assessed on the basis of the prevailing wind direction (as a precaution and in the estimation phase, the maximum size of the source area could be assessed).

The main migration pathway of silica dust can be due to erosion and transport by wind; in this case the exposure modes are dust inhalation (outdoor). The other mechanisms of transport (direct, volatilization and percolation) and exposure (dermal contact, ingestion) can be considered inactive. As for the receptors, in the first analysis, adults working on the site are to be considered as targets (on-site exposure factors for adults in industrial settings). In the second analysis, even if the first residence is located far (>4 km) from the extraction and accumulation areas, potential targets could be adults and children (offsite exposure factors in residential settings).

Thanks to the conceptual model and trying to evaluate the specific risk connected to silica presence in the investigated area, it was possible to assert that no specific onsite and off-site risk is due to quartzite and quartzite EW facilities exploitation. Indeed, the concentration of silica dust on site arising from RiskNet is $2.36 \cdot 10^{-4}$ mg/m^3.

The following data were used as feeding data for RiskNet:

- 10% of exploitable EW (quartzite) is assumed to the fine materials, thus, about the 77% of the fine fraction (318,000 t) can be assumed as respirable silica.
- The area interested by silica dispersion is approximately 2 km^2, and the silica concentration is about 7.7110^5 mg/kg.
- The potential residential receptors are 4 km far for the contamination source

3.3. Economic factors

As the three potential mining activities are not currently operating and there are no plans to activate them soon, it was considered to give a preliminary evaluation, thanks to a "soft and partial" CBA, stressing especially the estimation of potential revenues for kaolinitic gneiss, quartzite ornamental stones and the quartzite EW.

Data used for the estimation of potential revenues arises from field data (See Table 2 paragraph 3.1.a), whereas the data connected to commodity prices come from official price lists and info from local trade associations. In particular (Table 3.a), the estimation for the reserve of kaolinitic gneiss in about 3,765,000 m^3 (considering only the well-known Tre Fontane area), with an economic evaluation of near 3,768,765,000 €.

The kaolinitic indicated resources in about 22,027,600 m^3 (considering Tre Fontane, Rifreddo, Roballe and Envie areas) with a potential revenue of near 22,049,627,600 € and the kaolinitic inferred resources in about 11,290,000 m^3 (considering only Tre Fontane, Rifreddo and Envie areas) with a potential revenue of near 11,301,290,000 €.

Considering quartzite ornamental stones (Table 3.b), the potential exploitable material swings between 435,600 and 726,000 m^3 with an average of 580,800 m^3, equal to 4,065,600–5,808,000 m^2, with a mean hypothetical revenue which swings between 1,422,960,000 and 2,032,800,000 €.

Finally (Table 3.c), the quartzite EW are estimated in 2,250,000 m^3 (considering the existent EW facilities) with a potential revenue of near 607,500,000 € and can reach 4,940,000 m^3 (with a potential revenue of near 1,333,800,000 €), if the total quartzitic bodies present in Loc. Pian Martino and Pian Lavarino are exploited.

In particular, as for quartzite EW (to produce industrial minerals for ceramic and glass industries), the estimate quantities of potential exploitable ore deposit and the operating wastes (in case of restarting of quarry exploitation, reaching ca. 40,000 t/year), let us think about a plant which is able to treat ca. 150,000 t/year (40.000 t from current wastes and 110.000 t from dumps). Their exhausting should be possible within ca. 30 years.

Taking in to account the potential costs about CBA, it is possible to identify the following types of costs, given as an example only: extraction cost, construction cost, technology cost, operating costs, excavation tax, insurance costs, investments in plant and machinery.

Thinking about a total revenue (kaolinitic gneiss, quartzite EW and *Bargiolina* ornamental stone) which swings between 13,331,750,000 € and 25,416,227,600 € and a potential exploitation of at least 30 years for EW and more for kaolinitic gneiss, the exploitation of the three resources (programmed joined exploitation) is worth of consideration (Table 3.d).

3.4. Social and legislative factors

Some legislative issues, specific for the investigated area, must be faced in case of integrate exploitation of all the resources (natural and anthropic ones). Different Italian legislation must be used for, on the one side, kaolinitic gneiss and EW facilities (quartz used for ceramic and

SOURCE (MATRIX)	MIGRATION MODE	EXPOSURE WAY	EXPOSURE MODE	EXPOSURE TYPE	RECEPTORS
Superficial soil layer	EROSION DUE TO THE WIND (DUST)	DISPERSION IN AIR	DUST INHALATION	INDIRECT	ADULTS (workers on site - industrial), KIDS (residential off site)

Fig. 11. Conceptual model for Monte Bracco extractive site.

Table 3a
Economic evaluation of kaolinitic gneiss.

	Price per ton (€)	Bulk density (t/m^3)	Volume (m^3)	Mass (t)	Value (€)
Kaolinitic gneiss	455	2.2	3,765,000	8,283,000	3,768,765,000
Kaolinitic indicated resources	455	2.2	22,027,600	48,460,720	22,049,627,600
Kaolinitic inferred resources	455	2.2	11,290,000	24,838,000	11,301,290,000
Total					37,119,682,600

Table 3b
Economic evaluation of *Bargiolina* Quartzite ornamental stones.

	Price per m^2 (€)	Volume (m^3)	Area (m^2)	Value (€)
Bargiolina Quartzite ornamental stones				
Min potential exploitable value	350	435,600	4,065,600	1,422,960,000
Max potential exploitable value	500	726,000	5,808,000	2,032,800,000

Table 3c
Economic evaluation of quartzite EW.

	Price per ton (€)	Bulk density (t/m^3)	Volume (m^3)	Mass (t)	Value (€)
Quartzite EW	150	1,8	2,250,000	4,050,000	607,500,000
Quartzite EW Max pot. exploitable value	150	1,8	4,940,000	8,892,000	1,333,800,000
Total					1,941,300,000

Table 3d
Total hypothetical revenue evaluation of RM.

COMMODITY	Revenue (min; €)	Revenue (max; €)
Kaolinitic gneiss (Tre Fontane)	–	3,768,765,000
Kaolinitic gneiss (others)	11,301,290,000	22,049,627,600
Bargiolina Quartzite ornamental stones	1,422,960,000	2,032,800,000
Quartzite EW	607,500,000	1,333,800,000
Total	13,331,750,000	25,416,227,600

glass industries), and *Bargiolina* quartzite on the other side. A focus on Italian legislation (R.D. 1443/27, L.R. 69/78), important in case of integrate exploitation, is not in line with a scientific paper, thus it is not here included.

It is important to know that the three investigated resources (*Bargiolina*, quartzite EW and kaolinitic gneiss) are linked and their exploitation must be designed, programmed and carried out together. The correct management of *Bargiolina* quartzite is one of the main challenges for Public Administration, which aims at protecting the quartzite resource (that could be designated as Heritage Stone Resources, Pereira et al., 2015) and people involved in its exploitation. At the same time, the contemporary quartzite waste exploitation and transformation (thanks to a processing plant) and kaolinitic gneiss exploitation will guarantee, on the one side, new job places for local and qualified people, but will cause, at the same time, some troubles connected to a heavier road traffic. In case of integrated exploitation of the three resources a specific investigation about social impacts must be carried out.

4. Conclusion and future perspectives

The presented interdisciplinary (technical, social, economic, and environmental) approach, focus of the paper, is aimed to program a more responsible and sustainable exploitation of the natural resources, thinking about a concurrent exploitation of the natural (ore) and anthropogenic (extractive waste facilities) deposits of the investigated areas (landfill mining and enhanced landfill mining approach). Together with the exploitation of natural and anthropogenic deposits, it is mandatory to project and schedule the exploitation of SRM and by-products from ore dressing (circular economy approach).

A representative case study (Monte Bracco area – Northern Italy) has been presented to validate the interdisciplinary approach: the three different ore deposits of the Monte Bracco area can be exploited in an integrated way to enhance the productivity of each single deposit (natural or anthropogenic). Extractive waste facilities in potentially exploitable areas are the result of the past wrong planning: only the best portions of the ore body were exploited and, because of that, most of the potentially useful quarry benches were abandoned. Furthermore, in old dumps a large quantity of waste material is still present, from which it would be possible to exploit a considerable quantity of quartzite (2%), to be sold as *opus incertum* (Dino et al., 2005). Modern EW facilities (from ’90 to nowadays), which can be catalogued as not yet and/or completely rehabilitated dumps, have to be considered as spoils. The quantity of wastes disposed in old dumps, together with the potential EW produced during *Bargiolina* exploitation, should justify an industrial recover of the resource. Some advantages in exploiting EW facilities should be highlighted:

- current wastes do not have to be dumped anymore;
- a potential production of *opus incertum* using not exploited *Bargiolina* from rehabilitated dumps;
- the recovery EW from EW facilities will lead to better rehabilitation processes, higher safety condition for slope stability and the potential discovery of not exploited quartzite ore deposits in the EW dumping areas.

Together with EW management and recovery (pillar of EU policy about circular economy and landfill mining), the planning and concurrent exploitation of the other two natural resources present in the Monte Bracco area is crucial: kaolinitic gneiss and *Bargiolina* quartzite. Results arising from the study can be useful for a programmatic valorization of public properties and for a re-qualification of the territory setting: all the exploited materials should be used and commercialized, also the ones present in dumping areas.

Analytical investigations carried out on kaolinized gneiss have also shown interesting REE contents (especially Y), in line with the contents of deposits hosted by clay minerals worldwide (Borts et al., 2020). The tonnage, mineralogy and the easy accessibility of the ore deposit make it very attractive from a critical raw material perspective. At present time REE represent only a potential resource, whose possible exploitation will depend on mining policies and the strategic importance for the Italian and European industries in the future.

The sustainable exploitation of the Monte Bracco resources could guarantee a good impact in terms of environmental (thanks to a safer slope stability), economic (fees to be paid to Municipalities) and social returns (new job places connected to exploitation). But, together with positive returns, some negative one (in the short and midterm) must be faced (quartz dust production during the exploitation phase, noise, CO_2 emission due to logistics, and possible scarce acceptability of new exploitation by citizen).

Author contributions

Dino Giovanna Antonella: conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, supervision, validation, visualization, roles/writing - original draft; writing - review & editing.

Cavallo Alessandro: conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, software, supervision, validation, visualization, roles/writing - original draft; writing - review & editing.

Faraudello Alessandra: conceptualization, formal analysis, validation, roles/writing - original draft.

Rossi Piercarlo: conceptualization, formal analysis, validation, roles/writing - original draft.

Susanna Mancini: methodology, formal analysis, software, methodology. This new author was added because she has contributed to the drafting of the environmental impact chapter.

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References

Afum, B.O., Caverson, D., Ben-Awuah, E.A., 2019. A conceptual framework for characterizing mineralized waste rocks as future resource. Int. J. Min. Sci. Technol. 29, 429–435. https://doi.org/10.1016/j.ijmst.2018.07.002.

Ali, S.H., Giurco, D., Arndt, N., Nickless, E., Brown, G., Demetriades, A., Durrheim, R., Enrique, M.A., Kinnaird, J., Littleboy, A., Meinert, L.D., Oberhänsli, R., Salem, J., Schodde, R., Schneider, G., Vidal, O., Yakovleva, N.r., 2017. Mineral supply for sustainable development requires resource governance. Nature 543 (7645), 367–372. https://doi.org/10.1038/nature21359.

APAT, 2008. Agenzia per la Protezione dell'Ambiente e per i Servizi Tecnici, Italy. Criteri metodologici per l'applicazione dell'analisi assoluta di rischio ai siti contaminati (Methodological criteria for the application of the analysis absolute risk analysis to the contaminated sites). Available at. http://www.isprambiente.gov.it/files/temi/siti-contaminati-02marzo08.pdf. (Accessed 14 September 2018). Accessed on.

Arrobas, D., Hund, K.L., Mc Cormick, M.S., Ningthoujam, J., Drexhage, J.R., 2017. The growing role of minerals and metals for a low carbon future. World Bank. https://documents.worldbank.org/en/publication/documents-reports/documentdetail/207371500386458722/the-growing-role-of-minerals-and-metals-for-a-low-carbon-future. (Accessed 18 January 2021). accessed.

Ballou, R.H., 2007. The evolution and future of logistics and supply chain management. Eur. Bus. Rev. 19 (4), 332–348. https://doi.org/10.1108/09555340710760152.

Ballou, R.H., Gilbert, S.M., Mukherjee, A., 2000. New managerial challenges from supply chain opportunities. Ind. Market. Manag. 29, 7–18. https://doi.org/10.1016/S0019-8501(99)00107-8.

Banks, D., Younger, P.L., Arnesen, R.-T., Iversen, E.R., Banks, S.B., 1997. Mine-water chemistry: the good, the bad and the ugly. Environ. Geol. 32, 157–174. https://doi.org/10.1007/s002540050204.

Béjaoui, I., Kolsi-Benzina, N., Sappin-Didier, V., Munoz, M., 2016. Health risk assessment in calcareous agricultural soils contaminated by metallic mining activity under mediterranean climate. Clean 44 (10), 1385–1395. https://doi.org/10.1002/clen.201500512.

Bergek, A., Jacobsson, S., Carlsson, B., Lindmark, S., Rickne, A., 2008. Analyzing the functional dynamics of technological innovation systems: a scheme of analysis. Res. Pol. 37, 407–429. https://doi.org/10.1016/j.respol.2007.12.003.

Bjørn, A., Chandrakumar, C., Boulay1, A.M., Doka, G., Fang, K., Gondran, N., Zwicky Hauschild, M., Kerkhof, A., King, H., Margni, M., 2020. Review of life cycle-based methods for absolute environmental sustainability assessment and their applications. Environ. Res. Lett. 15 (8).

Blanchard, B.S., Fabrycky, W.J., 1998. In: Systems Engineering and Analysis, third ed. Prentice Hall College Div.

Blengini, G., Mathieux, F., Mancini, L., Nyberg, M., Cavaco Viegas, H., Salminen, J., Garbarino, E., Orveillon, G., Saveyn, H., Mateos Aquilino, V., et al., 2019. Recovery of Critical and Other Raw Materials from Mining Waste and Landfills; EUR—Scientific and Technical Research Reports. Publications Office of the European Union, ISBN 978-92-76-03391-2. https://doi.org/10.2760/494020 (online), 978-92-76-03415-5 (print); ISSN 1831-9424 (online), 1018-5593 (print).

Borst, A.M., Smith, M.P., Finch, A.A., Estrade, G., Villanova-de-Benavent, C., Nason, P., Marquis, E., Horsburgh, N.J., Goodenough, K.M., Cheng, X., Jindřich, K., Kalotina, G., 2020. Adsorption of rare earth elements in regolith-hosted clay deposits. Nat. Commun. 11 (1), 4386. https://doi.org/10.1038/s41467-020-17801-5.

Brown, R.J., 1979. A new marketing tool: life-cycle costing. Ind. Market. Manag. 8 (2), 109–113. https://doi.org/10.1016/0019-8501(79)90050-6.

Brown, T.J., Idoine, N.E., Raycraft, E.R., Shaw, R.A., Deady, E.A., Hobbs, S.F., Bide, T., 2016. World Mineral Production 2011-15. British Geological Survey, Keyworth, Nottingham, p. 96.

Burlakovs, J., Jani, Y., Kriipsalu, M., Vincevica-Gaile, Z., Kaczala, F., Celma, G., Ozola, R., Rozina, L., Rudovica, V., Hogland, M., 2018. On the way to "zero waste" management: recovery potential of elements, including rare earth elements, from fine fraction of waste. J. Clean. Prod. 186, 81–90. https://doi.org/10.1016/j.jclepro.2018.03.102.

Campopiano, A., Casciardi, S., Del Gaudio, M., Fioravanti, F., Lega, D., Ramires, D., 2007. Esposizione a polveri respirabili nelle cave di materiali calcarei: misura della concentrazione di silice cristallina. Prevenzione Oggi. Gennaio- marzo 3 (1), 19–31, 2007.

Careddu, N., Dino, G.A., Danielsen, S.W., Přikryl, R., 2018. Raw materials associated with extractive industry: an overview. Resour. Pol. 59, 1–6. https://doi.org/10.1016/j.resourpol.2018.09.014.

Cavallo, A., Dino, G.A., 2019. The Bargiolina, a striking historical stone from Monte Bracco (Piedmont, NW Italy) and a possible source of industrial minerals. Sustainability 11 (16), 4293. https://doi.org/10.3390/su11164293.

Chipera, S.J., Bish, D.L., 2002. FULLPAT: a full-pattern quantitative analysis program for X-ray powder diffraction using measured and calculated patterns. J. Appl. Crystallogr. 35 (6), 744–749. https://doi.org/10.1107/S0021889802017405.

Compagnoni, R., Rolfo, F., Groppo, C., Hirajima, T., Turello, R., 2012. Geological map of the ultra–high pressure Brossasco–Isasca unit (Western Alps, Italy). J. Maps 8, 465–472. https://doi.org/10.1080/17445647.2012.744367.

Danthurebandara, M., Van Passel, s., Vanderreydt, I., Van Acker, K., 2015. Assessment of environmental and economic feasibility of enhanced landfill mining. Waste Manag. 45, 434–447. https://doi.org/10.1016/j.wasman.2015.01.041.

Dino, G.A., Fornaro, M., Martinetto, V., Rodeghiero, F., Sandrone, R., 2001. Le risorse estrattive del Monte Bracco: valorizzazione mineraria e recupero ambientale. GEAM 104, 195–202.

Dino, G.A., Gioia, A., Fornaro, M., Bonetto, S., 2005. Monte Bracco quartzite dumps: chance of recovery as second raw material for glass and ceramic industries. In: First International Conference on the Geology of Tethys, vols. 12–14. Cairo University, Egypt, pp. 203–208. November 2005.

Dino, G.A., Rossetti, P., Perotti, P., Alberto, W., Sarkka, H., Coulon, F., Wagland, S., Griffiths, Z., Rodeghiero, F., 2018a. Landfill mining from extractive waste facilities: the importance of a correct site characterisation and evaluation of the potentialities. A case study from Italy. Resour. Pol. 59, 50–61. https://doi.org/10.1016/j.resourpol.2018.04.012.

Dino, G.A., Mehta, N., Rossetti, P., Ajmone-Marsan, F., De Luca, D.A., 2018b. Sustainable approach towards extractive waste management: two case studies from Italy. Resour. Pol. 59, 33–43. https://doi.org/10.1016/j.resourpol.2018.07.009.

Dondi, M., Raimondo, M., Zanelli, C., 2014. Clays and bodies for ceramic tiles: reappraisal and technological classification. Appl. Clay Sci. 96, 91–109. https://doi.org/10.1016/j.clay.2014.01.013.

ASTM, E1739-95e1, , ASTM International, West Conshohocken, P.A., 1995. Standard Guide for Risk Based Corrective Action Applied at Petroleum Release Sites.

ASTM, E2081-00, , ASTM International, West Conshohocken, P.A., 2015. Standard Guide for Risk Based Corrective Action.

European Commission, 2001. Communication from the Commission: Sustainable Europe for a Better World: A European Union Strategy for Sustainable Development. Working Paper Com, p. 264 final; European Commission, Brussels, 15.5.2001.

European Commission, 2005. Communication from the commission to the council and the European parliament draft declaration on guiding principles for sustainable development; working paper. COM 218 final; European Commission, Brussels, 25.5.2005.

European Commission, 2011a. Tackling the challenges in commodity markets and on raw materials. Brussels. COM, 2011) 25 final report. https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2011:0025:FIN:en:PDF. (Accessed 8 January 2021). accessed.

European Commission, 2011b. In: Guidance on Undertaking Non-energy Extractive Activities in Accordance with Natura 2000 Requirements. Brussels. https://op.europa.eu/en/publication-detail/-/publication/1ad3394e-de79-11e9-9c4e-01aa75ed71a1. (Accessed 3 February 2021). accessed.

European Commission, 2014. Report on national minerals policy indicators. In: Framework Conditions for the Sustainable Supply of Raw Materials in the EU. Brussels. https://ec.europa.eu/docsroom/documents/5562/attachments/1/translations/en/renditions/pdf. (Accessed 18 January 2021). accessed.

European Commission, 2015, 2015. In: Closing the Loop - an EU Action Plan for the Circular Economy. COM, Brussels, p. 614. final. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52015DC0614 (accessed March 2, 2021).

European Commission, 2017. Study on the review of the list of Critical Raw Materials – non-critical raw materials factsheets. DG Internal Market, Industry, Entrepreneurship and SMEs. Deloitte Sust., BGS, BRGM, TNO), p. 476.

European Commission, 2018. Report on critical raw materials and the circular economy, pp. 1–80. https://doi.org/10.2873/331561, 978-92-79-94627-1.

European Commission, 2020a. Study on the EU's list of critical raw materials, factsheets on non-critical raw materials. Final report. https://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en. (Accessed 2 February 2021). accessed.

European Commission, 2020b. Critical Raw Materials Resilience: Charting a Path towards Greater Security and Sustainability. COM, Brussels, p. 474, 2020. https://ec.europa.eu/docsroom/documents/42849. (Accessed 4 March 2021). accessed.

European Commission, 2020c. Communication from the Commission EUROPE 2020: A Strategy for Smart, Sustainable and Inclusive Growth. Working Paper. Com, 2010) 2020.

EUROSTAT, 2018. Reference database for detailed statistics on international trade in goods (Comext). https://ec.europa.eu/eurostat/web/international-trade-in-goods/data/database. (Accessed 12 January 2021). accessed.
Extractive Waste Directive 2006/21/EC. Directive 2006/21/EC of the European Parliament and of the Council of 15 March 2006 on the Management of Waste from Extractive Industries and Amending Directive 2004/35/EC.
Fields, S., 2003. The Earth's open wounds: abandoned and orphaned mines. Environ. Health Perspect. 111, 154–161. https://doi.org/10.1289/ehp.111-a154.
Flanagan, D.M., 2016. Silica, in 2016 minerals yearbook, 2019 (advance release), 66. U. S. Geological Survey, pp. 1–66, 15. https://www.usgs.gov/centers/nmic/silica-statistics-and-information. (Accessed 12 December 2020). accessed.
Fliess, B., Mård, T., 2012. Taking stock of measures restricting the export of raw materials: analysis of OECD inventory data. OCED Trade Policy Paper 140. https://doi.org/10.1787/5k91gdmdjbtc-en.
França, W.T., Barros, M.V., Salvador, R., et al., 2021. Integrating life cycle assessment and life cycle cost: a review of environmental-economic studies. Int. J. Life Cycle Assess. 26, 244–274. https://doi.org/10.1007/s11367-020-01857-y.
González-Corrochano, B., Esbrí, J.M., Alonso-Azcárate, J., Martínez-Coronado, A., Jurado, V., Higueras, P., 2014. Environmental geochemistry of a highly polluted area: the La Union Pb–Zn mine (Castilla-La Mancha region, Spain). J. Geochem. Explor. 144 (B), 345–354. https://doi.org/10.1016/j.gexplo.2014.02.014.
Goodenough, K.M., Schilling, J., Jonsson, E., Kalvig, P., Charles, N., Tuduri, J., Deady, E. A., Sadeghi, M., Schiellerup, H., Müller, A., Bertrand, G., Arvanitidis, N., Eliopoulos, D.G., Shaw, R.A., Thrane, K., Keulen, N., 2016. Europe's rare earth element resource potential: an overview of REE metallogenetic provinces and their geodynamic setting. Ore Geol. Rev. 72 (1), 838–856. https://doi.org/10.1016/j.oregeorev.2015.09.019.
Gray, N.F., 1997. Environmental impact and remediation of acid mine drainage: a management problem. Environ. Geol. 30, 62–71. https://doi.org/10.1007/s002540050133.
Grimalt, J.O., Ferrer, M., Macpherson, E., 1999. The mine tailing accident in Aznalcollar. Sci. Total Environ. 242, 3–11. https://doi.org/10.1016/S0048-9697(99)00372-1.
Gupta, A., Yan, D., 2016. In: Mineral Processing Design and Operation: an Introduction, second ed. Elsevier Inc., Amsterdam, p. 882.
Hartman, H.L., Mutmansky, J.M., 2002. In: Introductory Mining Engineering, second ed. John Wiley & Sons, Hoboken (New Jersey, USA), p. 592.
Helios Rybicka, E., 1996. Impact of mining and metallurgical industries on the environment in Poland. Appl. Geochem. 11, 3–9. https://doi.org/10.1016/0883-2927(95)00083-6.
Hennebel, T., Boon, N., Maes, S., Lenz, M., 2015. Biotechnologies for critical raw material recovery from primary and secondary sources: R&D priorities and future perspectives. N. Biotech. 32, 121–127. https://doi.org/10.1016/j.nbt.2013.08.004.
Herron, S., 2006. Industrial sand and sandstone. In: Kogel, J.E., Trivedi, N.C., Barker, J. M., Krukowski, S.T. (Eds.), Industrial Minerals and Rocks. Commodities, Markets, and Uses, seventh ed. Society for Mining, Metallurgy, and Exploration Inc., Englewood (Colorado, USA), p. 1548.
Hudson-Edwards, K.A., Macklin, M.G., Miller, J.R., Lechler, P.J., 2001. Sources, distribution and storage of heavy metals in the Rio Pilcomayo, Bolivia. J. Geochem. Explor. 72, 229–250. https://doi.org/10.1016/S0375-6742(01)00164-9.
Jolliet, O., Jolliet, A., Shaked, S., Crettaz, P., Saade-Sbeih, M., 2015. In: Environmental Life Cycle Assessment, first ed. CRC Press.
Jones, P.T., Geysen, D., Tielemans, Y., Van Passel, S., Pontikes, Y., Blanpain, B., Quaghebeur, M., Hoekstra, N., 2013. Enhanced Landfill Mining in view of multiple resource recovery: a critical review. J. Clean. Prod. 55, 45–55. https://doi.org/10.1016/j.jclepro.2012.05.021.
Kalantzakos, S., 2020. The race for critical minerals in an era of geopolitical realignments. Int. Spectator 55 (3), 1–16. https://doi.org/10.1080/03932729.2020.1786926.
Karaca, O., Cameselle, C., Reddy, K.R., 2018. Mine tailing disposal sites: contamination problems, remedial options and phytocaps for sustainable remediation. Rev. Environ. Sci. Biotechnol. 17, 205–228. https://doi.org/10.1007/s11157-017-9453-y.
Kinnunen, P.H.M., Kaksonen, A.H., 2019. Towards circular economy in mining: opportunities and bottlenecks for tailings valorization. J. Clean. Prod. 228, 153–160. https://doi.org/10.1016/j.jclepro.2019.04.171.
Kogel, J.E., Trivedi, N.C., Barker, J.M., Krukowski, S.T., 2006. Industrial Minerals and Rocks: Commodities, Markets and Uses. Society of Mining, Metallurgy and Exploration, Littleton, Colorado, p. 1565.
Lave, L.B., Cobas-Flores, E., Hendrickson, C.T., McMichael, F.C., 1995. Using Input-Output analysis to estimate economy-wide discharges. Environmental Science and 21Technology 29 (9), 420–426. https://doi.org/10.1021/es00009a003.
Liang, F., Sayed, M., Al-Muntasheri, G.A., Chang, F.F., Li, L., 2016. A comprehensive review on proppant technologies. Petroleum 2 (1), 26–39. https://doi.org/10.1016/j.petlm.2015.11.001.
Lim, M., Han, G.C., Ahn, J.W., You, K.S., Kim, H.S., 2009. Leachability of arsenic and heavy metals from mine tailings of abandoned metal mines. Int. J. Environ. Res. Publ. Health 6, 2865–2879. https://doi.org/10.3390/ijerph6112865.
Liu, H., Probst, A., Liao, B., 2005. Metal contamination of soils and crops affected by the Chenzhou lead/zinc mine spill (Hunan, China). Sci. Total Environ. 339, 153–166. https://doi.org/10.1016/j.scitotenv.2004.07.030.
Mancini, L., Sala, S., Recchioni, M., Benini, Lorenzo, Goralczyk, M., Pennington, D., 2015. Potential of life cycle assessment for supporting the management of critical raw materials. Int. J. Life Cycle Assess. 20, 100–116. https://doi.org/10.1007/s11367-014-0808-0.
Mathieux, F., Ardente, F., Bobba, S., Nuss, P., Blengini, G., Alves Dias, P., Blagoeva, D., Torres De Matos, C., Wittmer, D., Pavel, C., Hamor, T., Saveyn, H., Gawlik, B., Orveillon, G., Huygens, D., Garbarino, E., Tzimas, E., Bouraoui, F., Solar, S., 2017. Critical Raw Materials and the Circular Economy – Background Report, EUR 28832 EN. Publications Office of the European Union, Luxembourg, ISBN 978-92-79-74283-5. https://doi.org/10.2760/378123.JRC108710 (print),978-92-79-74282-8 (pdf), doi:10.2760/378123 (online),10.2760/977855 (print), JRC108710.
Mehta, N., Dino, G.A., Ajmone Marsan, F., Lasagna, M., Romè, C., De Luca, D.A., 2018. Extractive waste management: a risk analysis approach. Sci. Total Environ. 622–623, 900–912. https://doi.org/10.1016/j.scitotenv.2017.11.260.
Mehta, N., Cipullo, S., Cocerva, T., Coulon, F., Dino, G.A., Ajmone-Marsan, F., Padoan, E., Cox, S.F., Cave, M.R., De Luca, D.A., 2020. Incorporating oral bioaccessibility into human health risk assessment due to potentially toxic elements in extractive waste and contaminated soils from an abandoned mine site. Chemosphere 255 (126927). https://doi.org/10.1016/j.chemosphere.2020.126927.
Ministero dell'ambiente e della tutela del territorio, 2006. Gazzetta Ufficiale N. 88 of 14 Aprile 2006 Decreto Legislativo 3 Aprile 2006, N. 152"Norme in Materia ambientale." (Norms Concerning the environment.). (Accessed 14 September 2017). accessed.
Moss, R.L., Tzimas, E., Willis, P., Arendorf, J., Tercero Espinoza, L., 2013. Critical Metals in the Path towards the Decarbonisation of the EU Energy Sector. Publications Office of the European Union. https://doi.org/10.2790/46338.
Murray, H.H., 2006. Kaolin applications. Developments in Clay Science 2 (c), 85–109. https://doi.org/10.1016/S1572-4352(06)02005-8.
MWEI BREF, 2018. In: Garbarino, E., Orveillon, G., Saveyn, H.G.M., Barthe, P., Eder, P. (Eds.), Best Available Techniques (BAT) Reference Document for the Management of Waste from Extractive Industries. JRC Science for Policy Report. In Accordance with Directive 2006/21/EC. EUR 28963 EN, p. 722.
Nakamura, N., 1974. Determination of REE, Ba, Fe, Mg, Na and K in carbonaceous and ordinary chondrites. Geochem. Cosmochim. Acta 38, 757–775. https://doi.org/10.1016/0016-7037(74)90149-5.
Navidi Kashani, A.H., Rashchi, F., 2008. Separation of oxidized zinc minerals from tailings: influence of flotation reagents. Miner. Eng. 21, 967–972. https://doi.org/10.1016/j.mineng.2008.04.014.
Norris, G.A., 2006. Social impacts in product life cycles - towards life cycle attribute assessment. Int. J. Life Cycle Assess. 11, 97–104. https://doi.org/10.1065/lca2006.04.017.
OECD, 2018. Cost-Benefit Analysis and the Environment: Further Developments and Policy Use. OECD Publishing, Paris.
Pactwa, K., Woźniak, J., Strempski, A., 2018. Sustainable mining—challenge of polish mines. Resour. Pol. https://doi.org/10.1016/j.resourpol.2018.09.009 (in press), available online 25 September 2018.
Pepper, I., Gerba, C., Gentry, T., 2014. In: Environmental Microbiology, third ed. Elsevier Inc., Amsterdam, p. 728.
Pereira, D., Marker, B., Cooper, B.J., Schouenborg, B., 2015. Global heritage stone resource. In: Pereira, D., Marker, B.R., Kramar, S., Cooper, B., Schoeunborg, B. (Eds.), Book: Global Heritage Stone: towards International Recognition of Building and Ornamental Stones. Chapter: Introduction. https://doi.org/10.1144/SP407.18.
Plante, B., Benzaazoua, M., Bussiere, B., Kandji, E.H.B., Bouzahzah, H., 2015. Use of the EDTA in modified kinetic testing for contaminated drainage prediction from waste rocks: case of Lac Tio mine. Environ. Sci. Pollut. Control Ser. 22, 7882–7896. https://doi.org/10.1007/s11356-015-4106-6.
Pohl, W.L., 2011. Economic Geology Principles and Practice: Metals, Minerals, Coal and Hydrocarbons – Introduction to Formation and Sustainable Exploitation of Mineral Deposits. Wiley-Blackwell, Hoboken (New Jersey, USA), p. 663.
Pruett, R.J., Pickering Jr., S.M., 2006. Kaolin. In: Kogel, J.E., Trivedi, N.C., Barker, J.M., Krukowski, S.T. (Eds.), Industrial Minerals and Rocks. Commodities, Markets, and Uses, seventh ed. Society for Mining, Metallurgy, and Exploration Inc., Englewood (Colorado, USA), p. 1548.
Reichl, C., Schatz, M., Zsak, G., 2018. World mining data. In: Minerals Production, BMNT, Federal Ministry of Sustainability and Tourism and International Organizing Committee for the World Mining Congresses Vienna, vol. 33, p. 263. http://www.wmc.org.pl/sites/default/files/WMD2018.pdf. (Accessed 12 November 2020). accessed.
Schaider, L.A., Senn, D.B., Brabander, D.J., McCarthy, K.D., Shine, J.P., 2007. Characterization of zinc, lead, and cadmium in mine waste:implications for transport ,exposure ,and bioavailability. Environ. Sci. Technol. 41, 4164–4171. https://doi.org/10.1021/es0626943.
Schandl, H., Eisenmenger, N., 2006. Regional patterns in global resource extraction. J. Ind. Ecol. 10 (4), 133–147. https://doi.org/10.1162/jiec.2006.10.4.133.
Shams Fallah, F., Vahidi, H., Pazoki, M., Akhavan-Limudehi, F., Aslemand, A.R., Samiee Zafarghandi, R., 2012. Investigation of solid waste disposal alternatives in lavan island using life cycle assessment approach. Int. J. Environ. Res. 1, 155–164. https://doi.org/10.22059/ijer.2012.594.
Snell, M., 2011. In: Cost-benefit Analysis. A Practical Guide, second ed. Inst of Civil Engineers Pub., London, p. 295.
Stucki, M., Jattke, M., Berr, M., et al., 2021. How life cycle–based science and practice support the transition towards a sustainable economy. Int. J. Life Cycle Assess. 26, 1062–1069. https://doi.org/10.1007/s11367-021-01894-1.
Talavera Mendoza, O., Ruiz, J., Díaz Villaseñor, E., Ramírez Guzmán, A., Cortés, A., Salgado Souto, S.A., Dótor Almazán, A., Rivera Bustos, R., 2016. Water-rock-tailings interactions and sources of sulfur and metals in the subtropical mining region of Taxco, Guerrero (southern Mexico): a multi-isotopic approach. Appl. Geochem. 66, 73–81. https://doi.org/10.1016/j.apgeochem.2015.12.002.
Tiruta-Barna, L., Benetto, E., Perrodin, Y., 2007. Environmental impact and risk assessment of mineral wastes reuse strategies: review and critical analysis of approaches and applications. Resour. Conserv. Recycl. 50 (4), 351–379. https://doi.org/10.1016/j.resconrec.2007.01.009.

UNFCCC. United, 2015. Nations Framework Convention on Climate Change. Paris Agreement. UNFCCC, New York, NY, USA.
Weisz, H., Duchin, F., 2006. Physical and monetary input-output analysis: what makes the difference? Ecol. Econ. 57 (3), 534–541. https://doi.org/10.1016/j.ecolecon.2005.05.011.
West, D.N., 2020. Clays. In: Mineral Commodity Summaries. U. S. Geological Survey, pp. 48–49. https://pubs.usgs.gov/periodicals/mcs2020/mcs2020-clays.pdf.
Whitney, D.L., Evans, B.W., 2010. Abbreviations for names of rock-forming minerals. Am. Mineral. 95, 185–187. https://doi.org/10.2138/am.2010.3371.
Wills, B.A., Finch, J.A., 2015. In: Wills' Mineral Processing Technology: an Introduction to the Practical Aspects of Ore Treatment and Mineral Recovery, Eight Edition. Elsevier Inc., Amsterdam, p. 498. https://doi.org/10.1016/C2010-0-65478-2.
Wong, M.H., 2003. Ecological restoration of mine degraded soils, with emphasis on metal contaminated soils. Chemosphere 50, 775–780. https://doi.org/10.1016/S0045-6535(02)00232-1.
Wood, D.A., Joron, J.L., Treuil, M., Norry, M., Tarney, J., 1979. Elemental and Sr isotope variations in basic lavas from Iceland and the surrounding ocean floor. Contrib. Mineral. Petrol. 70, 319–339. https://doi.org/10.1007/BF00375360.