

Review

Sustainability in the Minerals Industry: Seeking a Consensus on Its Meaning

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Abstract: Sustainability science has received progressively greater attention worldwide, given the growing environmental concerns and socioeconomic inequity, both largely resulting from a prevailing global economic model that has prioritized profits. It is now widely recognized that mankind needs to adopt measures to change the currently unsustainable production and consumption patterns. The minerals industry plays a fundamental role in this context, having received attention through various initiatives over the last decades. Several of these have been, however, questioned in practice. Indeed, a consensus on the implications of sustainability in the minerals industry has not yet been reached. The present work aims to deepen the discussion on how the mineral sector can improve its sustainability. An exhaustive literature review of peer-reviewed academic articles published on the topic in English over the last 25 years, as well as complementary references, has been carried out. From this, it became clear that there is a need to build a better definition of sustainability for the mineral sector, which has been proposed here from a more holistic viewpoint. Finally, and in light of this new perspective, several of the trade-offs and synergies related to sustainability of the minerals industry are discussed in a cross-sectional manner.

Keywords: sustainability; sustainable development; minerals industry; mining; mineral processing; life cycle thinking; mineral resources; globalization; technological innovation

1. Introduction

Mining—considered here in a broad sense, which comprises both mineral exploitation and processing operations—has been historically one of the industrial activities that have contributed the most to the economic development of humanity, serving as the basis of several industries including energy, construction, chemical, pharmaceutical, automotive, electronics, aerospace, ceramics, cosmetics, detergents, glass, metals, paints, paper, plastics, and fertilizers, among others [1,2]. Indeed, mankind continues to rely heavily on metals due to their multiple important characteristics—malleability, ductility, electrical and thermal conductivity, and durability—which make them a very good and cost-effective option for several applications [3]. Such metals are mainly obtained from primary resource extraction [3,4], and this scenario will certainly remain unchanged in the next several decades. This will continue as such despite all recent efforts towards improving the recyclability and circularity of metals contained in the discarded products [4], as well as other sources of waste associated to mining activities, such as the case of building and construction materials.

Contrasting to the unconstrained growth of the mining industry in the past, there are governments and institutions that have been promoting the vision of the Club of Rome [5] which postulates that economic development based on the continuous increase in extraction of primary mineral resources is not sustainable [6]. The result is that the concepts of sustainability and of sustainable development (SD) have since become progressively incorporated as a priority topic in regional and national government agendas in several developed and developing countries [2]. There is also a general recognition that

mining and mineral processing operations present, in general, low conversion efficiencies, high energy intensity, large volumes of tailings and emissions, besides a number of impacts [7] whose magnitudes generally increase as the scale of production is intensified and run-of-mine ore grades drop [8]. All of these contribute remarkably to the ongoing debate whether mining may or not be rigorously considered sustainable.

When compared to the other resource industries such as forestry, aquaculture, and agriculture, the mining industry is perceived as one of the least committed to SD [9]. This is a cause of concern for this sector since these other industries are no stranger to unsustainable practices, such as fish overexploitation [10]. In fact, the finite nature of mineral resources on a worldwide scale is generally highlighted as one of the main reasons behind such perception of the intrinsic unsustainability of the minerals industry. A particular mining operation generally lasts from about one to several decades, until a point is reached when exploiting the mineral resource becomes unfeasible either due to the characteristics of the mineral deposit, the metal prices, or even due to government instabilities or impacts to communities and the environment [3]. Therefore, the dark history of inappropriate practices in the field, primarily based on a development model exclusively focused on profits in the extraction of primary natural resources with no rehabilitation plan in the surrounding environment affected by the extractive activity is no longer acceptable and now requires a proper plan for development and management [11].

The overall result is that the minerals industry has been subjected to growing pressures by governments and society in general towards the adoption of more sustainable practices. To better understand the potential impacts, either positive or negative, that may be related to the extractive activities, as well as responding to these pressures, there has been a significant growth of interest on the topic in the mining industry [2,9,12]. This interest has also grown in terms of academic research on how mining relates to sustainability and SD, in particular over the last two decades [13]. Examples of these are several initiatives that have been proposed to deal with different aspects of sustainability in the mining sector, although their effectiveness has been questioned [10,12]. As such, confusion and lack of consensus remain in the interpretation and translation into practice of the concepts of sustainability and SD, not only in general [14–16] but also in the particular case of the mining industry [9,12,13,17]. In this context, the present work reviews and analyzes critically the literature, aiming to answer the following research questions (RQ):

RQ 1: How has sustainability been conceptualized and approached in general, and in the minerals industry context?

RQ 2: Which are the sustainability challenges for the minerals industry from a more comprehensive perspective, considering each of the dimensions of sustainability and their interactions (trade-offs and synergies), as well as the different spatial and temporal domains?

2. Methods

A research methodology has been established to answer the questions raised in Section 1, covering the literature published in the last 25 years, which has been crucial for the consolidation of the science of sustainability in general and in the minerals industry context. This literature survey was mainly conducted through Brazil's Ministry of Education (CAPES) Journals Portal, an academic metasearch engine which encompasses databases and search engines such as ScienceDirect (Elsevier), Scopus (Elsevier), SpringerLink (Springer), ProQuest, JSTOR Archival Journals, SciELO.ORG, among several others. From this search a total of 3177 peer-reviewed papers (789 from 1992 to 2009 and 2388 between 2010 and mid-July 2017, besides e-mail alerts from the CAPES Portal since then), written in English, were initially encountered, being classified by their relevance according to criteria presented in Figure 1. Additional references were also searched and reviewed along with the preparation of the present work, considering relevant secondary sources and key authors identified after the first iteration of search and selection of references for further analysis (Figure 1). It is important to clarify that there were many publications focused on issues that fall outside the scope of this work along the literature survey process.

One set of publications focused nearly exclusively on Life Cycle Assessment (LCA) has been found, which has been classified into different topics and will be considered for a future review. Another set of references was automatically discarded from his title and abstract content since they addressed other issues that were misinterpreted as being relevant to the mining industry (e.g., “data mining”). The selection of “relevant” articles for this review was subjected to the authors’ criteria, whereby it is possible that important publications related to the subject may have been unintentionally omitted. However, the authors attempted to cover as much as possible most of the cross-cutting topics related to the sustainability of the minerals industry, especially focused on large-scale operations in a holistic context (including examples of case studies, when necessary), and giving greater attention to the exploitation and processing of primary mineral resources.

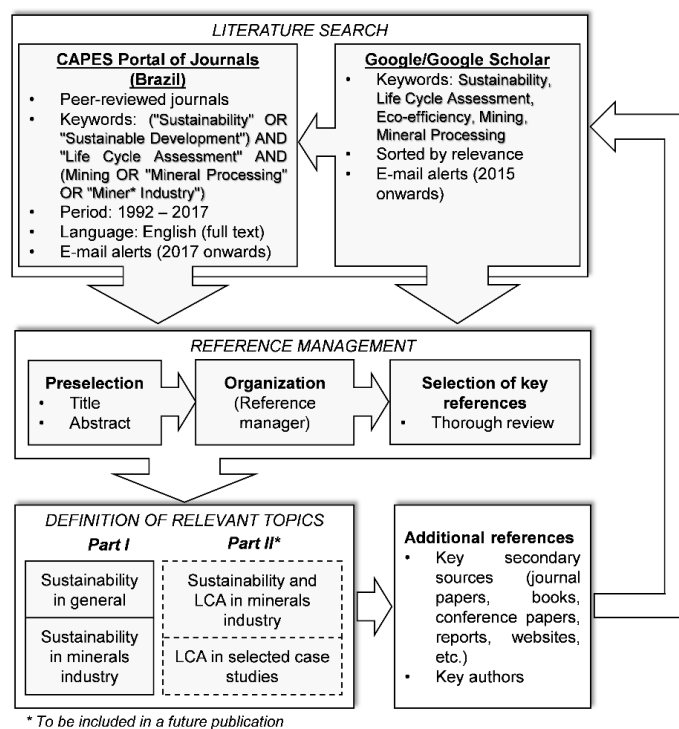


Figure 1. Methodology of the literature survey.

The first part of the present review (Sections 3–5) is mainly concerned with the critical analysis of the historical narratives and theories concerning the sustainability and the SD and how these have been incorporated in the minerals industry context, aiming answer RQ 1, while establishing a basis for the second part of the review (Section 6). In the latter, a broader representation of the sustainability for the minerals industry is proposed, where synergies and trade-offs involved from this perspective are addressed and discussed in an integrative and cross-sectional fashion to answer RQ 2. Some limitations and perspectives in this research field are also identified throughout the text and, finally, some concluding remarks (Section 7) are presented.

3. The Sustainable Development Paradigm

Growth and economic development have been dominant paradigms since the first industrial revolution that started in England nearly 200 years ago, remaining so until the first half of the 20th century [18,19]. At about this point in time questions have started to be raised related to this model of development, which has been associated with drastic changes such as the intensive exploitation of resources and the continuous technical and technological innovation. This period of strong human intervention on the biosphere, named *Anthropocene*, allowed growing the standard of living of mankind

and a greater support for the continuous growth of the world's population. However, it is well-known that this occurred at the expense of large inequality, in both income and resource consumption, between the developed countries and those still under development, as well as of a new scenario of environmental degradation of global proportions [19].

In this context, the Club of Rome was established in the late 1960s. This interdisciplinary organization, with a strong scientific background, studied the worldwide issue from a more systemic perspective, aiming to understand the complexity of the interactions between the different elements (technical, social, economic and political) that are part of the global system delimited by finite resources [5]. The resulting document of the Club of Rome's work, called *The Limits to Growth*, had a great impact in the international political agenda and was recognized as a first "sign of alarm" to mankind on the urgent need to change the prevailing development paradigm. It is important to acknowledge, however, that previous studies had already warned about the implications and relationship between population growth, poverty and resource use, such as the *Essay on the Principle of Population* by Thomas Robert Malthus in 1798, the theoretical work of Harold Hotelling on the optimal rate of non-renewable resource exploitation in 1931, and *The Tragedy of the Commons* by Garrett Hardin in 1968 [16,19]. The Club of Rome's publication served as a basis for what would be later built as the Sustainable Development (SD) paradigm, although, in practice, the emphasis on economic development has remained dominant globally [18]. Indeed, the majority of practical solutions to pollution prevention remain conservative, such as of *end-of-pipe* type [19,20], even though these alternatives have been recognized by some companies as costly and inefficient [20].

The United Nations (UN) has been on the leading role in spreading this new paradigm of development worldwide, initially at the Stockholm Conference in 1972, and later with the creation of the Brundtland Commission and the introduction of the concept of Sustainable Development as the one that "*seeks to meet the needs and aspirations of the present without compromising the ability to meet those of the future. Far from requiring the cessation of economic growth, it recognizes that the problems of poverty and underdevelopment cannot be solved unless we have a new era of growth in which developing countries play a large role and reap large benefits.*" [21]. That definition highlighted the need to give greater emphasis to the needs of both present generations—especially those of the poorest people—and future generations, that is, intragenerational and intergenerational equity. This leading role of the UN was maintained for several years, with the Rio Conference (Eco-92 or Earth Summit) in 1992, where nearly 180 countries started to commit formally to the adoption of principles and actions for a transition towards SD. The action plan from this conference (Agenda 21) was revised in further conferences [22], including the Rio+10 in 2002 and the Rio+20 in 2012. The social aspect of SD, in particular, the concept of intergenerational equity, was already included in the original document by The Brundtland Commission. Despite this, the majority of the companies which prepared themselves for signing the *Business Charter for Sustainable Development*, written by the International Chamber of Commerce for Eco-92, had only a limited grasp of the fundamental logic behind the SD. Indeed, only aspects of the *greening* of the economic activities were prioritized, leaving on the side other aspects, such as political, ethical and social, which also directly impact the economy and the environment [23]. As such, the UN established the Sustainable Development Goals (SDGs), which helped to consolidate the social dimension of this new development paradigm. At first, eight SDGs [24] were defined, being later amended to a total of 17 [25], as part of the UN 2030 Agenda for SD. The eradication of poverty has been recognized as a key goal in the social arena [19].

The discussion led by the UN in relation to SD has also been focused on matters that are directly related to the extraction of natural resources. For instance, the emphasis on mitigation of climate change through the incorporation of clean energy sources in the global energy matrix started to gain more visibility and impact through the consolidation of the Intergovernmental Panel on Climate Change (IPCC) in 1988, and of important international treaties such as the United Nations Framework Convention on Climate Change (from Eco-92), and the Kyoto Protocol. In 2007, the UN Environment Programme (UNEP) launched the International Resource Panel (IRP), which is a group of specialists

that, in analogy to the IPCC, aims at informing and supervising the policymakers, the industry and the society in general regarding critical issues associated to the use of resources in a global scale.

The SDGs have been one of the multiple frameworks proposed by organizations to promote SD on a global scale. Two alternative SD structures have also been suggested and deserve attention. The first is *The Earth Charter*, which is a group of fundamental principles aimed at “*building a just, sustainable, and peaceful global society for the 21st century*” [26]. The other is *The Natural Step* (TNS), which is a model that supports the planning and assessment of human activities from a more holistic perspective, aiming at the appropriate use of resources to satisfy the basic human needs globally, without increasing the concentration of substances extracted from the earth’s crust or produced by society, or causing the physical impoverishment of ecosystems [27].

4. Conceptualizing Sustainability

Meeting the SDGs simultaneously is quite complex, given the multiple trade-offs involved between them. Besides that, several of these goals can result in an increasing use of resources that include water, energy, and materials. Nevertheless, the recognition of the strong ties between human well-being, economic prosperity, and a healthy environment has been one of the highlights of this approach [19], which shows a continuous evolution in the SD paradigm with the incorporation of other concepts. A decade after the SD concept was introduced, the concept of sustainability was proposed, whose definition has been largely attributed to J. Elkington [23], although it has been claimed that this concept was informally proposed long before, particularly within forestry and economy [16]. This definition, established in the context of business management, was based on the three *bottom lines* or pillars of SD: economic, social and environmental. These have also been expressed as PPP or P3 (People, Planet and Profit), being the term *Profit* later modified to *Prosperity* in the Rio+10 Conference [28]. Years later, through the UN 2030 Agenda, two more Ps (Peace and Partnership) were added [29].

The concept of sustainability based on the Triple Bottom Line (TBL) model is, perhaps, the most widely used to date, although methodological difficulties have been recognized in its implementation, especially regarding the approach of an equilibrium and a proper integration of the three dimensions. Indeed, Elkington [23] himself recognized that the major challenge resides in the interaction between the bottom lines, defined by the author as *shear zones*: eco-efficiency (economic–environmental interaction), environmental justice (environmental–social interaction) and business ethics (social–economic interaction). It has been further identified that the social and environmental dimensions are not easily quantifiable in practice when compared to the economic aspects so that this lack of clarity can result in their definitions as a function of their financial feasibility [30]. Some authors have proposed adding extra pillars to sustainability or to SD based on the TBL paradigm. For instance, it has been proposed to include the *Institutional* or *Governmental* component [26,31], the *Ethical* component [32], the *Technological* component [18], or a time component [33] from an intergenerational perspective. The latter aims at guaranteeing the long-term continuity of integration of these dimensions, such as perceived in the definition of SD by the Brundtland Commission. It has also been pointed out that the definition of sustainability “pillars” is inappropriate, at least for the economic and the social ones, since both can be seen as two sides of the same coin, that is, well-being [16]. Other authors [6,34] consider that these interactions between bottom lines, often represented as intersecting circles in a Venn Diagram, may be better understood as concentric circles, that is, *anthropogenic* systems (technological, political, economic and social) contained in a larger system, the *ecosphere*, which includes the biota and the abiotic resources, aiming at representing sustainability on the basis of a model that is more ecologically and scientifically realistic.

Besides the TBL model, other conceptualization of sustainability started being developed from the beginning of the 1990s, based on the idea of the different *assets*, given the growing need to relate the capital stock to nature and, therefore, to the SD paradigm. This was how some publications of the World Bank started to introduce the expressions: “man-made capital” (or manufactured), “natural capital”, “human capital” and “social capital” [35,36]. Later, Bebbington [35] suggested adding yet another dimension, the “cultural capital”. Although the author recognizes that this capital cannot

and should not be quantified, it is important to emphasize its importance beyond the social capital, in particular in regional and rural development contexts. Years later, the Five Capitals Model (FCM) would be formally defined, which is an alternative sustainability model that is especially promoted by the Forum for the Future [36–38], in which the financial capital is added to the other four capitals introduced by the World Bank. The FCM has some similarities to the TBL model, although it divides the social aspects in individuals (human capital) and groups (social capital), identifying explicitly the dimension that is related to the “artificial environment” or *technosphere* (manufactured capital). The FCM has been represented graphically as concentric circles [37] (p. 141), where the larger circle represents the “natural capital”, equivalent to the ecosphere. In analogy to the SDGs, models such as TBL and FCM have contributed by highlighting the social aspects (and its subdomains), which certainly are of most difficult quantification and integration with the other aspects of sustainability.

Evidently, SD and sustainability are two different concepts which are not straightforward to define and that are being continuously built, thanks to the new perspectives and approaches. Unfortunately, these two have often been confused. This is understandable, given the growing relevance of this subject worldwide and for different sectors of society (academic, corporate, governmental, NGOs, etc.), which becomes evident from the growing volume of publications on sustainability and SD in general [13]. Indeed, some interpretations suggest that sustainability goes beyond SD. For instance, SD is interpreted as a path or process through which principles, approaches, strategies, and policies are developed and implemented to achieve a “sustainable society” [14,26], or an “ideal dynamic state” which is supposed to be sustainability [33]. Even sustainability is conceived as a wider and more relevant concept than SD, in the sense that the latter has been historically associated to the idea of unlimited physical growth (population, use of resources, GDP, etc.) in a world with constrained resources [34]. Philosophically, both terms have also been identified [39] as extreme positions: sustainability as an “environmental-preservationist” view, and SD as a “prudentially conservationist” one. In that sense, SD can only lead to sustainability if the anthropocentric perspective is extended to a broader one, that is, *ecocentric*.

In addition to the multiple definitions and interpretations of sustainability, there has also been an increasing number of concepts, paradigms and methods related to SD and sustainability during recent decades, such as Eco-efficiency, Life Cycle Thinking, Cleaner Production, Zero Waste, Cradle-to-Cradle, Design for Environment, Green Chemistry, Eco-design [26,40], Decarbonization, Circular Economy, and many others, as well as synergies between them, which reflect the urgent need for a better understanding of the complex problems caused by the “development” of our anthropogenic system, with serious environmental consequences. A sustainable solution that supports the creation of a *symbiotic* relationship or synergy between these systems (natural and anthropogenic, in a more general sense), based on a systemic thinking, instead of a reductionist approach, becomes necessary.

5. Overview of Sustainability in the Minerals Industry

5.1. Introduction

Sustainability has been commonly approached in mineral and metal processing from two perspectives: one is focused on the resource use and management, and the other on minimizing the impacts associated with the production process [41]. Furthermore, mining operations have been recently introduced in a more systemic scope, through the incorporation of the *life cycle* concept, which has been considered from two different standpoints which intersect the mine operation stage (Figure 2): the *Life Cycle of the Mining Project*, which is related to the life of a mine and includes the stages from exploration until mine closure [3,41–45] or even post-rehabilitation [46,47], and that of the *Life Cycle of the Product* that is associated to the value chain of a particular mineral resource or *commodity*, also referred to as Life Cycle Thinking [2,6,8,14,41,43,45,48]. In addition, more recently, a consensus has been reached in respect to the different scales through which sustainability may be approached in the minerals industry. In terms of timescale, sustainability of this sector may be analyzed from present

to future generations [10,14,41,48,49], and in terms of spatial or geographic domains, from local to global [7,8,10,14,44], or even extending to the controversial and still technically, economically and commercially distant outer space mining [4,50]. Such domains are compatible with the SD definition from the Brundtland Commission, and with the dynamics of the minerals industry in the context of a globalized economy, respectively. Climate change has also been progressively recognized as a key subject in the minerals industry, both from the relevance of this environmental issue globally and from its strong connection with the mining activities [4,8,51,52].

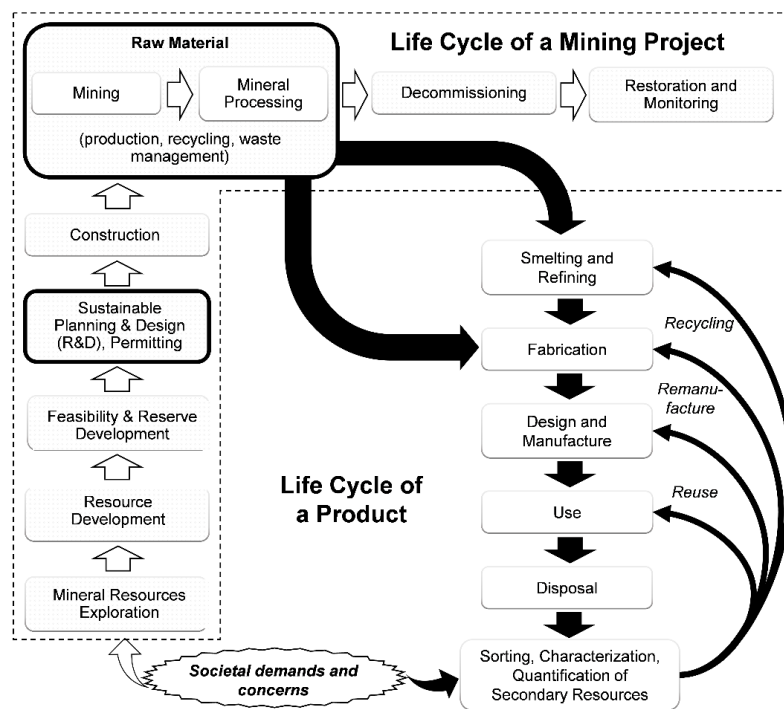


Figure 2. “Life cycle” concept in the sustainability context of minerals industry operations. Modified after: [2,41,47–49].

On the other hand, some critical factors for obtaining and maintaining the “social license to operate” have been identified:

- The involvement of all stakeholders, including communities, local authorities, workers, government, industry, NGOs, universities, shareholders, contractors, etc. [2,43,53];
- The definition of strategies for an effective communication and participation of the public, creating good long-term and collaborative relationships between the stakeholders [43,54,55]; and
- A fairer distribution of the costs and benefits that arise from mining activities [48,55].

It has also been argued [56] that this social license is directly related to the technological aspects and, therefore, must be considered from the conceptual design stage of a mining operation through R&D, in order to anticipate possible concerns and expectations from stakeholders in relation to the incorporation of new technologies, according to the different contexts (political, geographic, geological and social) of each operation. Besides the “social license to operate”, the social dimension has been gaining more attention in the minerals industry context through the concept of “responsible mining”, in which this latter is considered more comprehensive in terms of the production chain than the former, although it cannot deal with matters such as the consumption and discarding of products, the total (not the relative) reductions in the use of resources (water, energy, etc.), the availability of secondary mineral resources and the *rebound effect* [57].

There are several cases of conflicts in different scales between mining companies and their stakeholders, but there have also been reported some good initiatives. Examples of the latter are the partnership between Placer Dome Inc. and the World Conservation Union in Niger in rehabilitation through the cooperative work with the community, the creation of partnerships between Rio Tinto and local and indigenous communities [43,54], and Anglo American's organizational culture of "Zero Harm", that aims at raising the operational safety standards [58]. Other cases worthy of mention from mining companies that have contributed to poverty alleviation and empowering of small-scale miners are the Sadiola Gold Mining Project of Anglo Gold in Mali and the Placer Dome's Las Cristinas Project in Venezuela [59].

Bond [44] introduced a new concept in the context of the relationship between mining companies and communities. The author considered that the minerals industry should be more proactive, beyond the TBL, aiming to create and maintain conditions for a "*positive and sustainable peace*" with the communities potentially affected by its operations, through a joint work to promote violence- and conflict-free coexistence in all scales and forms, that is, structural, cultural or social violence. In that sense, it has been argued [60] that some large-scale mining operations may enhance risks and conflicts with communities (including artisanal miners), which seem not always to be visible or accounted for as potential negative impacts generated directly or indirectly by these companies.

5.2. Sustainability Frameworks in the Minerals Industry Context

Several frameworks have been suggested since the 1990s for analyzing sustainability from the perspective of the minerals industry. These have been proposed by several groups representing different projects and initiatives (identified by a series of abbreviations such as ICMM-GRI, ITSPM, MMSD, MAC-TSM, etc.), and are analyzed as follows.

Although the minerals industry was a notable absentee in the Eco-92 Conference, there was a broader general acceptance from that event onwards of the principle that *the polluter pays for environmental damage* [61]. Indeed, Agenda 21 highlighted the need to establish specific guidelines for the development of natural resources [62,63]. In this context, the *Berlin Guidelines* emerged as a deliverable from the 1991 Berlin Round Table on Mining and the Environment established by the UN and the German Foundation for International Development. These guidelines [62] defined fundamental principles for mining throughout its life cycle, such as: regulatory frameworks, environmental management, socioeconomic impact assessment, continuous participation of the communities and stakeholders, and technology transfer for environmental impact mitigation, among others [62,63]. Thus, the sustainability and SD concepts became particularly relevant on a global scale after the Eco-92, and started to gain relevance at governance level in the minerals industry context through initiatives such as the Berlin Guidelines that were mentioned. This may have strongly influenced the minerals industry to be progressively more concerned with social and environmental aspects of its operations in the following years, through various initiatives and by joining efforts among its members at different geographic scales. In Canada, for instance, the contribution of the Mining Association of Canada (MAC) with the aim of promoting the sustainability in the major mining companies of the country is worth mentioning. In that sense, the MAC led two important strategies: the "Whitehorse Mining Initiative" (WMI), which started in 1993/1994, and the subsequent "Towards Sustainable Mining" (TSM), which was launched in 2004. The WMI allowed the consolidation of the Leadership Council Accord, which defined a policy focused on aspects of sustainability of the mineral activities in Canada [12]. The TSM, on the other hand, was consolidated as a series of principles and performance indicators for the minerals industry, focusing on management issues related to planning crisis, energy and greenhouse gases, mining tailings, indigenous populations and communities, biodiversity conservation, and health and safety [12,64]. In general, the WMI has been considered more holistic than the TSM, since the first was conceived with greater participation of stakeholders, while the second has been more systematic, although only focused in limited aspects of sustainability [12].

In a global scale, one of the first initiatives was the consolidation of the International Council on Metals and the Environment (ICME) in 1991, which represented several countries and metal producing companies, aiming to incorporate better environmental and safety practices throughout the metal life cycle [61]. In 1998, some of the largest mining companies gathered with the aim of finding a new path towards sustainability. This resulted in the creation of the Global Mining Initiative (GMI) in 2000. This association requested to the International Institute for Environment and Development (IIED), through the World Business Council for Sustainable Development (WBCSD), a study to identify the global challenges of the sector through a participative process with different individuals and organizations. The results of this process were published as a series of recommendations which defined the scope of the Mining, Minerals, and Sustainable Development (MMSD) Project, which began in 2000, extending to 2002, being led by the IIED. The main deliverable of this project was a comprehensive final report called *Breaking New Ground* [49], in which a set of SD principles based on four dimensions—that is, using the TBL concept and adding the *governance* component—was adopted. These principles were recommended to be applied in an integrated and democratic fashion in decision-making, considering the mineral sector in a wider scope in terms of the benefits that it can generate to present and future generations [49].

The MMSD Project has also been object of criticism [65]. It has been argued that the project, despite having been presented as inclusive in respect to the affected communities, indigenous organizations, and NGOs, was predominantly established by industry. Partially in response to this lack of engagement between the mining companies and some communities affected by mining activities, a network, named Mines and Communities, was established in 2001, through which *The London Declaration* was written, which makes a series of criticisms related to the lack of transparency of the minerals industry in its “sustainable mining” initiatives [65]. This episode demonstrates the difficulty in establishing constructive dialogues between the mining companies and some local communities, particularly when the latter have been historically affected by mining projects and, therefore, do not trust in any initiative that comes from this industrial sector towards making their practices more sustainable.

One year after the start of the MMSD project, the International Council on Mining and Metals (ICMM)—an international organization that aims at improving the sustainability in mining operations and their associated production chains—was constituted. The ICMM could be interpreted as an improved version of the ICME, establishing, in 2003, ten SD principles that were identified on the basis of the results of the MMSD Project [66], as well as using some paradigms such as Life Cycle Thinking and TBL, including the *governance* dimension [3]. These principles were revised in 2015 [67], and have been incorporated voluntarily in the sustainability agenda of several of the largest mining companies as well as regional organizations of the mining and metallurgical sectors. There was another initiative at that time by professionals from the mining sector, who adopted a formal commitment with a transition towards a more sustainable future by signing *The Milos Declaration* in 2003 during the 14th Annual Meeting of the Society of Mining Professors and the following International Conference on Sustainable Development Indicators for the Mining Industry [68].

The ICMM has been working collaboratively with some communities in countries where its members operate, and has also strengthened partnerships with different organizations at a global level (World Conservation Union (IUCN), International Commission on Large Dams (ICOLD), International Labor Organization (ILO), International Trade Union Movement (ICEM)). Indeed, the ICMM has created a partnership with the Global Reporting Initiative (GRI) in regard to the development and adoption of specific guidelines for the elaboration of sustainability reports by its member companies [7,66]. However, the application of these guidelines by the mining companies, through their sustainability reports, has been criticized, in particular concerning the environmental sustainability reporting. On the one hand, they omit detailed information on geological and technological aspects [66], which are particularly relevant to the mineral sector, given the multiple sources of uncertainty and variability—such as those associated to the ore characteristics, market behavior, type of technology, etc.—which can affect the performance indicators of the operations. On the other hand, there is a large

variability in relation to the number of indicators and also in respect to the level of aggregation of the information associated with these indicators in both spatial (site, commodity, region, country, etc.), and time (weeks, months, and years) scales [69]. All of these questions reduce the transparency and make comparisons difficult in regard to the management of critical environmental issues such as the energy usage [66,69].

Thus, it has been recommended that the ICMM-GRI guidelines be applied to each specific mine site [66] in an operational-level decision, and in different spatial scales (mine site, organization, region) when the level of decision is more critical, such as in the long-term planning of a mine, the development of novel technologies, and the introduction of new installations [69]. It has also been observed [69] in these sustainability reports that there are no clear methodologies which explain how the sustainability indicators are effectively taken into consideration in the decision-making process of mining companies in order to make their operations more sustainable. Nevertheless, responding to the growing demands from society and to the commitment to the principles of ICMM, several mining companies remain publishing sustainability reports based on the GRI standards [44], which are being periodically updated and, more recently, being aligned with the principles of the UN Global Compact (another global corporate responsibility initiative that supervises the elaboration of sustainability reports) [66], with the aim of stimulating and aligning the advance of corporations in general with the SDGs agenda established by the UN.

During the Rio+20 Conference, the ICMM launched a series of documents with the aim of focusing the discussion on the contribution of the mineral and metallurgical sectors to sustainable development, rather than in how to make mining sustainable [70]. Moreover, the final document from the Rio+20 Conference *The Future We Want* stated that this sector may be more proactive in promoting inclusive development through initiatives that help to eradicate poverty, to integrate SD dimensions and to change production and consumption patterns [71]. However, putting in practice these SD objectives has been particularly challenging in some countries where natural resources abound and, at the same time, various conflicting situations, namely slow economic growth, limited diversification in the economic activities, corruption, oppression and greater economic volatility, converge [45]. In the case of artisanal and small-scale mining (ASM), it has been pointed out that several of these operations usually do not adopt SD principles [7,47]. Small-scale gold mining is, perhaps, the one that has received the most attention, since its strong expansion worldwide after the booming of gold prices in the past decade [72,73]. Such operations quite commonly rely on the extraction of gold using the amalgamation technique with mercury, which has a series of environmental and human health risks [59,73]. The informality of these operations in developing countries is quite high [72,74,75], which is critical for the sustainability of this mining sector. There are global and voluntary initiatives such as the Alliance for Responsible Mining and Fairtrade International, which are attempting to contribute to the formalization and development of ASM in some regions of Latin America and sub-Saharan Africa [72,76]. However, there are some critiques to these schemes, as well as a series of challenges—several of them rooted in a poor territorial governance—that need to be addressed so that these initiatives have a truly transformative impact on ASM, particularly for the poorest miners who are mostly informal [76–78]. On the other hand, there is recent evidence that room exists for some large-scale mining companies to better align themselves with the objectives of SD. An unfortunate example of this is the collapse of two tailings dams in the operation by Samarco in Mariana, Brazil (owned by Vale and BHP, both companies associated to ICMM), which has been identified as the largest environmental disaster caused by mining in the country [79].

In general, initiatives such as GMI, ICMM, the MMSD Project, among others, have been recognized in assisting the consolidation of the concept of sustainability in the minerals industry context [53,58]. Indeed, the SD principles established by the ICMM, besides various others general structures available (UN Global Compact, ISO standards, GRI, etc.), have helped mining companies to approach and manage particular aspects of sustainability [13]. However, it is questioned to what extent these guidelines and the sustainability reports based on them are aligned with the priorities and values of all stakeholders and with the SD of the local communities. In other words, these guidelines may be insufficient to guide mining companies

towards global sustainability in their operations [13,80]. Petrie [7] highlighted that the ICMM efforts are still far from influencing the behavior of the entire value chain in the case of minerals and metals. A recent study [58] analyzes how sustainability has been approached in the mineral sector based on an extensive analysis of sustainability reports from ICMM member companies as well as some academic research work. The authors defined three levels of sustainability, namely Perpetual Sustainability, Transferable Sustainability and Transitional Sustainability, and found that the sustainability agenda of the sector tends to be placed in an intermediate position (Transferable Sustainability), where the TBL concept is typically incorporated. However, it was also found that the highest level of sustainability (Transitional Sustainability), related to the intergenerational impacts along the production chain and also to the post-mining activities, is still rarely addressed. Indeed, this level of sustainability is presently associated to two concepts: Life Cycle Assessment (LCA) and “transitional development”, that is, development of local communities and of the economy of countries supplying minerals, facilitating the transition to more sustainable activities in the long term.

Some sustainability approaches in the minerals industry have been based on the FCM structure. McLellan et al. [41], for instance, used the FCM as theoretical background—recently expanded to “Six Capitals Model”, which has the added “Intellectual Capital” or intangibles of an organization based on knowledge [81]—and techniques such as the risk assessment of processes (Hazard and Operability Studies—HAZOP), to propose a tool for decision-making called SUSOP[®] (SuSustainable OPERations) (SUSOP Pty Ltd, Brisbane, Australia). The aim was to rigorously and widely approach the aspects of SD in the choice of alternatives for the design and management of mining projects, under the premise that the design phase is where the greatest opportunities to reduce the impacts and improve sustainability lie, especially with innovative developments and the use of the best available technologies. This approach matured over the last decade and has also been extended to the operation stage in mineral processing [82]. The framework was consolidated as a tool for the sustainable design of mining projects, having been applied in a number of case studies [83,84] and currently commercialized by JKTech Pty Ltd.

The previous approach is innovative due to the incorporation of aspects of sustainability in mining operations, in contrast to the business-as-usual scenario. However, its scope is limited, making it difficult to understand the advances towards sustainability in scales beyond the gates of a company or of a mining project. This is relevant, given the global character of most mining activities [10], with exception made perhaps for the construction and building materials. As such, Moran and Kunz [10] proposed a broader scheme to understand the advances in terms of SD for the minerals and energy sectors. They established a hierarchical structure that involves different spatial scales, from the global context down to the operational, so this last one can include both the case of a conglomerate of corporations or even a single unit operation. This model has been informally validated through interactions from various sectors (industry, government, and communities), and its applicability is still being explored. The authors also proposed adopting the concept of “Operating Sustainably” in contrast to the concepts of “Sustainable Mining” or “Responsible Mining”, where the former is defined in terms of the value that mining operations can generate from a perspective of production chain and use (and reuse) of the materials (Life Cycle Thinking). Giurco and Cooper [8], on the other hand, proposed a model which considers and integrates four key aspects related to sustainability in the mineral sector: primary and secondary mineral resources, technologies employed for extraction and processing, use and service provided by minerals in their final products, and rates of production and consumption. The authors suggested that each of these aspects may be approached in different geographical scales and sustainability dimensions based on the FCM, for which a conceptual framework called Mineral Resources Landscape has been proposed, where technological and governance domains are explicitly considered. However, the schematic representation of this framework makes it difficult to understand the implications of the concept of sustainability in the minerals industry context. Nevertheless, the authors demonstrated the conceptual application of this model through an example of deep sea mining in Australia [8].

Although the FCM has been widely used in the context of the minerals industry, it has shown limitations in dealing with aspects related to governance, which must be considered in the different

scales, that is, local, regional [80] as well as global [11]. Besides the FCM, the TBL has also been used as the basis of some representations of sustainability in the mineral sector. One of the first scientific publications related to quantification of sustainability in the minerals industry using this model is the work by Azapagic [2]. The author also used the knowledge previously consolidated by the MMSD Project and the GRI guidelines to propose a series of economic, social and environmental sustainability indices, individually and integrated into these three dimensions at a corporate level. Worrall et al. [9] also used this sustainability knowledge as well as criteria from the forestry and agricultural sectors, in the development of environmental, sociopolitical and economic indices, with the aim of giving greater support to the management of the final stages of the life cycle of mining projects, in particular the case of rehabilitation of areas degraded by mining.

Basu and Kumar [11], on the other hand, proposed a sustainability model based on an extension of the TBL, where the three pillars are supported by a “block” that represents governance, an additional element that integrates and helps to create a balance of the three bottom lines. All of this structure is supported by a “foundation block” of innovation and best practices of technological implementation. This conceptual representation is called Innovation and Technology Driven Sustainable Performance Management (ITSPM) and contributes in considering explicitly the relevance of the technological aspects in the sustainability context of the minerals industry. However, this approach established a hierarchy between these components, which is not useful to understand the complex interactions involved in them. The authors also consider the stage of design in the life cycle of the mine as the one in which the greatest opportunities of technological innovation exist, highlighting also the need to specify the technological implementation in the sustainability reports from companies. Laurence [17] also proposed a sustainability structure based on the TBL, to which the dimensions of “Safety” and “Efficiency” were added. The first is related to the adoption of safety practices, proper communication systems, training and education in the company. The second is concerned with the efficient exploitation of the mineral resource, for instance, extending the life of mines by exploitation of low-grade ores. This approach emphasizes some aspects of sustainability that are specific to the minerals industry and that, according to the author, have not been properly dealt with. However, it can become confusing in terms of the interpretation of each of the domains of sustainability and their interactions. This framework is also restricted to the geographical frontiers of a company and to the traditional vision of the mineral resource that is focused exclusively on primary ores. Another limitation of this structure is the disregard of the governance dimension, previously consolidated in the context of mining by the MMSD Project and the ICMM.

Recently, some SD principles specific for the mineral exploration phase [85] were formulated, which consider social, economic, environmental, governance and technological (“*responsible use of technologies*”) aspects. Technological innovation is also highlighted as a priority question in this approach, although it is only analyzed to a limited extent. It is evident that technological innovation plays a key role in the further stages of the life cycle of the mine, for instance, the operation phase [45], which extends for a long time and where there is certainly greater interaction with the natural environment and, consequently, with the neighboring communities. In addition, more recently, Villeneuve et al. [29] adopted a general methodology based on UN SDGs, besides a combination of multiple tools, to evaluate the sustainability of a mining project in Canada at its planning stage. Besides the TBL, the ethical and governance dimensions are incorporated into this framework, and the cultural dimension is added later in an updated tool version. However, this approach presents some limitations associated with its conceptualization, such as its general nature and its application in restricted geographic scales. Thus, some key aspects of the sustainability of the mineral sector, such as the role of technological innovation and the Life Cycle Thinking, are not deepened.

In summary, there are different interpretations of sustainability and of SD in the minerals industry (Table 1), which have been largely based on the original definition from the Brundtland Commission and in either one of the two main sustainability frameworks: TBL and FCM. Although there are some points of convergence regarding the need to adopt a more systemic approach to sustainability

in the mineral sector in different domains and contexts, there is still disagreement regarding which dimensions of sustainability must be explicitly considered. There is a consensus on the importance of the environmental, economic, social and, more recently, the governance aspects in the public and private levels. However, it is the present authors' opinion that the role of responsible and sustainable technological innovation for the minerals industry has been largely underestimated (Table 1). The lack of a general understanding of this component as a fundamental pillar of sustainability, as well as the multiple interactions between sustainability dimensions and scales involved, could help explain why there is not yet an effective implementation of sustainability in practice by the mineral sector. It is interesting to note (Table 1) that the incorporation of the *Life Cycle* concept helps to make the management of secondary resources more relevant in the mineral sector. Life Cycle Thinking (LCT), in particular, highlights the management of wastes that are generated along the production chain (*cradle-to-grave* or *cradle-to-cradle*), but it does not necessarily help focusing in the management of tailings and rock waste generated directly by the mining activities. This probably occurs because the life cycle of any product usually starts in the stage of mine operation (Figure 2), that is, from the exploitation of the resource ("cradle"), where the management of impacts in the other stages of the Mining Project Life Cycle is often overlooked.

Table 1. Comparison of selected approaches for sustainability/SD in the minerals industry context.

Sustainability/ SD Approach	Main Foundations	Sustainability Dimensions ¹		Concerned with Secondary Resources?	Spatial/ Geographic Domain	Temporal and "Life Cycle" Domains
		Dimensions	Hierarchy in Bottom Lines?			
Sustainability and SD in the primary extraction [14]	Brundtland Definition, TBL, TNS, LCT	1, 2, 3 (5 as subdimension and weakly addressed)	No	Yes	Local to global (unit process, mine site, company, nation, world)	Present to future generations; project (rehabilitation)/product life cycle
MMSD Project SD Principles [49]	Brundtland Definition, TBL, LCT	1, 2, 3, 4 (5 as subdimension)	Yes (<i>Strong Sust.</i>)	Yes	Local to global (mine site, region, nation)	Present to future generations; project/product life cycle
ICMM SD Principles [67]	MMSD Proj., TBL, GRI, LCT	1, 2, 3, 4	No	Yes	Local (mine site, company)	Project/product life cycle
MAC-TSM [12,64]	Brundtland Definition, GRI	1, 2, 3 (specific issues of each dimension)	No	Yes (tailings management)	Local to national (mine site, company, Canada)	Present to future generations
SD indicators for minerals industry [2]	Brundtland Definition, TBL, MMSD Proj, GRI, LCT	1, 2, 3	No	Yes	Local (large-scale mining companies)	Present to future generations; project/product life cycle
ITSPM [11]	Brundtland Definition, TBL, MMSD Proj.	1, 2, 3, 4, 5	Yes	No	Local (company, mining project)	Present to future generations; project life cycle (design)
Sustainability criteria and indicators for legacy mine land [9]	Brundtland Definition, TBL, MMSD Proj., ICMM-GRI, others	1, 2, 3, 4	No	Yes (land rehabilitation)	Local and regional (state)	Present to future generations; project life cycle (restoration and monitoring)
SUSOP® [41,83]	FCM, TBL, HAZOP, ICMM Principles, LCT	1, 2, 3 (4 and 5 partially addressed)	No	Yes	Local (company, mining project)	Project life cycle (planning, design, operation); product life cycle
Sustainable mining practices [17]	TBL	1, 2, 3, 5 (5 not explicit and weakly addressed)	No	No	Local (company, mine site)	Project life cycle (operation)
Mineral Resources Landscape [8]	FCM, LCT, PESTEL analysis	1, 2, 3, 4, 5	No	Yes	Local to global (mine site, nation, world)	Product life cycle
Progress of minerals and energy industries towards SD [10]	Brundtland Definition, FCM, LCT	1, 2, 3, 4, 5 (dimensions not formally stated; 5 weakly addressed)	No	Yes	Local to global (unit process, company, region, nation, world)	Present to future generations; project/product life cycle
SD principles for mineral exploration [85]	SD guidelines, expert consultation and consensus	1, 2, 3, 4, 5 (5 weakly addressed)	No	Yes (efficient resource use for waste management)	Local (mine site, company)	Project life cycle (exploration, rehabilitation), product life cycle
Tool for SD assessment in a mining project [29]	Brundtland Definition, UN SDGs, ISO 26000, others	1, 2, 3, 4 (<i>Ethical</i> and <i>Cultural</i> pillars also added)	No	Yes (land rehabilitation, reuse, recycling)	Local to national	Present to future generations; project life cycle

¹ Sustainability dimensions: 1 = Environmental; 2 = Social; 3 = Economic; 4 = Governance; and 5 = Technological Innovation.

A recent review [64] of some sustainability structures proposed for the mineral sector, that is, GRI-ICMM, ITSPM, MMSD Project, Azapagic [2] and the MAC-TSM initiative, suggests that there are limitations in these approaches. These include the underestimation of synergies and trade-offs between the sustainability dimensions, the difficulty in dealing with the shortage of resources, the need to explore the sustainability of the sector beyond the frontiers of the organization and in different time and spatial domains, and the need to build a definition of sustainability that goes beyond the Brundtland's definition. However, the authors of that review proposed neither a new definition for sustainability, nor a more in-depth discussion with respect to its dimensions and interactions between them in the context of the minerals industry. These are the topics that will be analyzed and discussed in the following section.

6. Sustainability Challenges and Opportunities for the Minerals Industry: A Complex Multi-Dimensional and Multi-Scale Network of Interactions

6.1. Introduction

As noted in Section 4, previously established concepts and models such as SD and FCM have been progressively developed and incorporated in sustainability science from a predominant economic and anthropocentric perspective. While this can make the transition to sustainability easier, it can lead to misinterpretations, giving greater attention to economic aspects (as in the business-as-usual model) and deepening the current ecological imbalance and social inequity. Nevertheless, recent studies [80,86] support the idea that FCM is suitable for sustainability related to mining activities. In fact, Eggert [86] argued that: *“in order to achieve sustainability, the degradation or depreciation must be offset with investments in new capital, and to achieve SD, the net effect of degradation and investment must be a sustainable increase in the stock of capital, which is the sum of all forms of capital”*. This particular view of sustainability and SD, which tends to consider that capital forms may be interchangeable, is commonly identified in the literature as *Weak Sustainability*, whilst the other view, the *Strong Sustainability*, emphasizes nature as fundamental and even irreplaceable by other “capitals” [16]. It is clear that some forms of capital cannot be replaced, especially in mining activities, but this is not always considered by the FCM, which makes it inconvenient to apply in practice [49]. To maintain harmony with previous research and terminology and avoid further confusion and ambiguity, we refer to “Sustainability” and to each of its components as bottom lines, pillars, domains, elements, dimensions, or any equivalent term other than “capitals”. This is in line with the vision previously adopted by the MMSD Project [49], but now formally incorporating a fifth dimension to sustainability. Thereby, in the forthcoming discussion on sustainability challenges in the minerals industry, a perspective based on the following key interacting elements has been adopted:

- Society (community, workers, NGOs, etc.);
- Economic System (or Economy);
- Natural Environment (Ecosphere = Geosphere + Biosphere);
- Technology (Artificial Environment, Artefacts or Technosphere); and
- Governance (including both public/political and private/corporate leadership).

A discussion on the sustainability challenges for the minerals sector is carried out as follows based on these five dimensions and their interactions. However, given the discussions presented on the different perspectives of sustainability in general (Section 4), as well as those applicable in the context of the mining industry (Section 5), a scheme is proposed for interpreting the sustainability related to this sector (Figure 3). All five dimensions of sustainability previously mentioned have been included, which are positioned along the circular arrow whose beginning and end correspond to the natural environment. Indeed, such interactions between nature and society have led to the creation of these “human constructs”, which have been progressively critical in the developments of the civilizations until today: the economic system, the governance, and the technology. All these components interact

and must be balanced in different scales of time and spatial location. As such, sustainability in the minerals industry must embrace each one of these scales, otherwise, it could be said that sustainability cannot be guaranteed. This would lead to a *Weak Sustainability*, which is depicted in Figure 3 as the dotted areas.

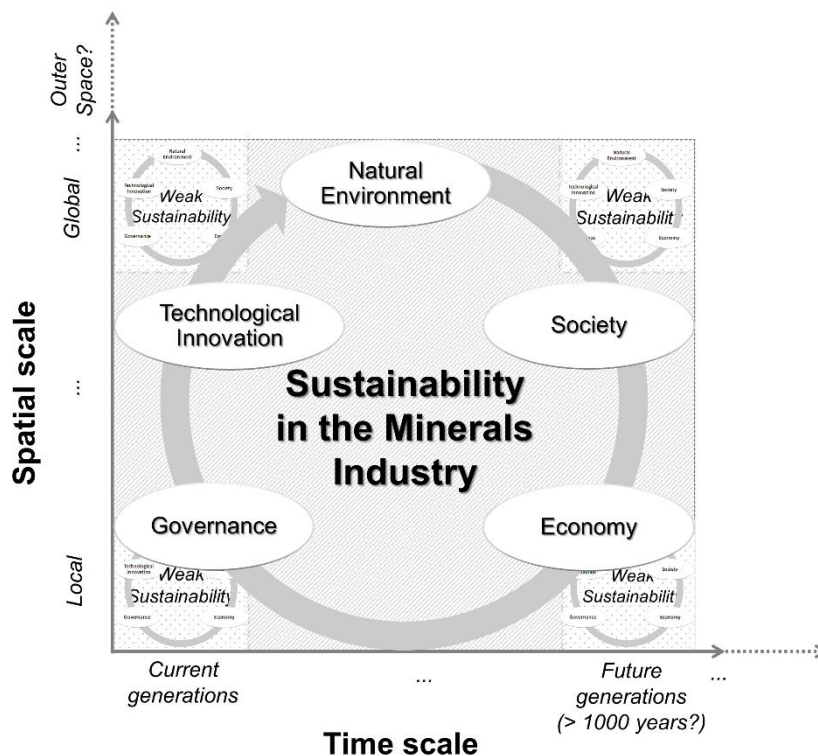


Figure 3. Schematic representation of sustainability in the minerals industry, incorporating: TBL concept (extended to fully integrated five dimensions), the local-to-global domain of the activity, the natural environment as the support of human constructs (circular arrow), and the intra- and intergenerational equity (Brundtland Commission) or temporal domain. Dotted areas represent “weak” sustainability.

This conceptualization aims at reconciling the different views of sustainability that have emerged in the last few decades, including the one based on the TBL, the one that considers the ecosphere as the basis of all systems (that is, the beginning and the end, considering the ecological limits of the natural environment, such as in The Natural Step and the MMSD Project approach), as well as the definition of SD according to the Brundtland Commission, which includes an intragenerational and intergenerational time scale, that is, long-term time horizon. This circular interpretation of sustainability was inspired by the work of Lozano [33], with modifications, such as the inclusion of the additional “bottom lines” (governance and technological innovation), as well as the geographical and spatial location, which covers the different scales, from the local, for instance the mine site or a unit operation, to the global. As such, it includes all the stakeholders involved in these different scales. The concept of sustainability represented hereby could be also applied to the exploitation of oil and gas, and be used as a baseline to establish more constructive dialogs between the different stakeholders in respect to sustainability in the minerals industry, as well as a ground for further development of sustainability indicators in this sector within or beyond the existing frameworks (Table 1).

6.2. Natural Environment Preservation

Mining activities must be carried out so as to minimize all possible impacts that can be caused to the natural environment during all stages of its life cycle, through an effective and proactive environmental management. This strategy should go beyond meeting local environmental standards,

given the global scope of these activities, as well as the wide variability of environmental legislation worldwide, particularly in developing countries where it is not often as strict [43]. The environmental impacts caused by mining are often associated with the physical changes in the mining area, as well as to the impact of the activity on the soil, water, and air. The soil can be, potentially, impacted in different ways. For instance, tailings containing chemical reagents as well as heavy metal wastes can contaminate the soil and water by natural processes such as erosion, rains, and flooding, thus affecting the ecosystems nearby [3]. This becomes critical given the unpredictable nature of such events globally due to climate change. Alteration in natural landscape is unavoidable in mining, and this can impact the environment and create discomfort to the population, in particular when communities already inhabit the area where a new mining project is to be established. However, this impact can be mitigated from the very beginning of the operation and after its closure, through the restoration of the degraded area, to preserve natural species as well as the soil for a future activity. In underground mining the landscape and soil can also be impacted by land subsidence, depending on the topography of the area and its surroundings [87]. Impacts from mining activity associated to deforestation have also been reported [80].

As the consumption and demand for natural resources increase and the run-of-mine ore grades drop, mining projects are pressed towards increasing their scale so that potentially impacted areas and mining waste volumes will increase accordingly. Tailings can be disposed in different forms, preferentially removing a significant part of the water associated to them (up to about 70–80% of solids, compared to 30–50% of solids in current operations), but the most common method remains disposal in tailings dams [79]. Considering the growing trend in mining waste generation in a business-as-usual scenario, it is possible that the risk of collapse of these dams will increase, being this the main source of environmental—and, perhaps, socio-environmental—disasters associated to mining activities [79,88]. That is why effective on-site waste management is critical to the sustainability of the minerals industry. A recent study [79] suggests that the collapsing of tailings dams is more strongly related to governance rather than technological aspects. As such, the presence of a robust regulatory environment is a key factor in preventing these disasters. This requires a greater commitment from the mining companies to meet high standards of safety related to waste management and mine area rehabilitation in the context of each region, which can be planned from the design stage of the mine and processing plant and executed until the end of the productive cycle. An outstanding example of that is the operation of the McLaughlin mine in California, which is now a natural preservation area [61,79].

Given the potential increase in capital and operating costs associated to better waste management, the development of a mine should not be justified in mineral deposits that are not profitable enough or when the area has particularly fragile environment [79]. On the other hand, under certain circumstances such as the Chilean context, disposal of mining tailings at higher solids concentrations is not necessarily more operationally expensive than conventional technologies, and may even bring additional benefits in terms of water recovery [89]. Recently, a new hierarchy has been suggested [90] for an efficient and proactive management of waste rock and tailings. It is based on the strategies of reduction, reprocessing, stockpiling, reuse and remediation, which allow dealing with these materials not as a problem, but rather as future economic and environmental opportunity. This has become even more critical given the high incidence of premature mine closures [17], which has caused the abrupt interruption in the life cycle management of these operations. A possible economic advantage of using these wastes as “resources” is the potential reduction in processing costs, since the tailings are already deposited on the ground surface [90,91] and have fine sizes, thus reducing a significant part of the processing costs associated to blasting and comminution.

The impacts on water resources are also varied, in both quantitative and qualitative terms. The first is due to depletion, while the second is associated to increase in turbidity, conductivity, contamination by ions, elements and chemical compounds associated to the processed ores and reagents used in the process [3]. The demand for water can be very large during the lifetime of a mine, especially in mineral processing [89], as well as in dust control, depending on several factors such as: climate conditions,

mineralogy and ore grade, scale of operation and proportion of water recovered in product(s) and tailings [92]. Efficient water management strategies aimed to minimize its local demand through technologies that allow reducing or even eliminating its consumption and further treatment, as well as maximizing its recovery and reuse [45] are, therefore, an important future challenge for the minerals industry, especially in fragile areas where there are shortage and competition for this vital resource. In that context, the integrated optimization of both water and energy has become particularly relevant and is only recently being addressed, for example, in cases such as the need to use seawater from remote sources in mining operations developed in arid zones of Chile [89]. In respect to the water quality, one of the most important impacts is the Acid Mine Drainage (AMD), which is caused by the oxidation of sulfide minerals contained in rocks and tailings exposed to the contact with water. AMD can be mitigated, for instance, through bioremediation and the incorporation of fully automated wastewater treatment facilities [3,20].

Different types of atmospheric emissions may affect the air quality, in particular during a mine operation. In general, the most important emissions are SO_x, NO_x, CO and other gases associated with the use of fuels. Particulate material emissions are also liberated, especially during the initial stages of the process (drilling, blasting, stockpiling, comminution, etc.), where the material presents relatively low moisture content. Greenhouse gases emissions are also associated to mining, through the consumption of fossil fuels in transportation and power generation [4,7,93], blasting with explosives [93], and also through fugitive methane emissions of varying intensity in coal extraction, depending on the mining method, depth of the mine, coal characteristics and gas content in the mineral deposit [87]. Nevertheless, mining industry can also help mitigating climate change, for instance by making available mineral resources for the development of clean technologies [4], as well as in carbon capture through reforestation of areas affected by mining. The effective implementation of the latter at regional scale has been questioned, but it has also been suggested to improve it through greater involvement with local communities, aiming to achieve a fairer distribution of responsibilities and economic benefits associated with a potential global carbon trading scheme [94].

More recently, the vulnerability and adaptability of mining operations to the effects of climate change started being approached [51,52,92,93]. These potential risks must be considered well before the beginning of a mining operation. For instance, in the global production of copper, where a significant part of the resources is located in areas with high risk of water shortage, exploitation operations can become unfeasible [51,92]. This is particularly relevant in the context of developing countries with growing mining activity within their territories, which, coupled to the risks of water scarcity and other socio-environmental concerns in these regions, have even led, for example, to recent radical positions such as the banning of metal mining in El Salvador [51]. However, the interest in this topic by the mineral sector is still limited, probably due to the lack of confidence in climate science, to the perceived distance in time of the predicted impacts, and also to the lack of long-term planning vision [52]. Nevertheless, a framework has been recently proposed [51] that aims to deepen discussions and research around the climate change-mining nexus.

A recent trend has been identified to give more attention to the efficient management of energy, water and wastes in the mining operations [7,45,85], which may be associated to the fact that these impacts may become even more critical from the standpoint of sustainability owing to the progressive decline in average run-of-mine ore grades [45]. This is, indeed, a global reality rather than a theoretical and local concern, at least according to what mining companies report [95]. The trend towards highlighting the reduction of environmental impacts per tonnage of product and not in absolute terms has also been observed. Such approach would lead to misinterpretations in relation to the management of these impacts, since efficiency improvements are challenged by the *rebound effects* associated to the rate and the magnitude of the use of natural resources, as a function of the demand for consumption of goods and services [41].

The growing interest in adopting a systemic vision to deal with the challenges of sustainability has motivated the appearance of new interdisciplinary and transdisciplinary areas of research. For instance,

the complex relationships between mankind and the environment are being studied and modeled at multiple scales, through the analyses of the interdependences involved in the management of different natural resources: energy, minerals, water, soil and food [57,96–105]. There are also ongoing debates on the management of mineral resources from a more holistic standpoint (Figure 2), which considers the potential scarcity of some mineral resources for future generations, and strategies for recycling and efficient use of resources.

6.2.1. Resource Availability and Criticality

Economy trends from decades ago have been supported by uncontrolled exploitation of natural resources. The growing demand for these resources has made some of them, in fact, “critical” in the sense of their overexploitation [106]. The term “critical material” has been coined in the lexicon for a long time, gaining popularity since shortly before the World War II, through the U.S. Strategic and Critical Materials Stock Piling Act of 1939 [107]. In the case of metals, the concept of criticality has gained relevance from the standpoint of the imbalance between their supply and demand [108]. Further, the degree of criticality of a nonfuel mineral has been recently defined considering criteria such as supply risk, vulnerability to supply restriction and environmental implications [107,108]. Additionally, concepts such as criticality and scarcity have been related to the value that society has placed on particular resources in terms of their usefulness [7]. As such, one of the most critical resources is energy, on which relies heavily the socio-economic development and whose growing production may not meet the current and future global demands, at least in the next two decades. On the one hand, energy consumption is expected to grow as the population increases, as well as does its standard of living. Energy consumption becomes even more critical considering that most energy sources are still non-renewable. Moreover, the global oil production is approaching its peak in the exploitation of the rich and easily extractable resources, and similar trends have also been observed for the gas and coal extraction. On the other hand, there is a high demand for energy and mineral resources in the development of alternative energy sources [106].

The discussion about availability versus scarcity is still controversial from the standpoint of sustainability of mineral and energy resources and has been usually approached from two contrasting views, based on Tilton’s work [109–111]: the “Fixed Stock” and the “Opportunity Cost” paradigms. The former is usually defended by ecologists (the “pessimists” or “concerned”) and considers the mineral resources as unreplaceable at a long-term so that future generations would not be deprived of their access. The second paradigm is often supported by economists (the “optimists” or “unconcerned”), and does not deny that an exhaustion of the mineral resources will occur. However, under this paradigm, it is argued that temporary scarcity leads to a greater technological development that will facilitate recovery of low-grade ores, increase in the production rate and the replacement by other materials [14,41,110,112,113]. However, within the opportunity cost paradigm, there are some uncertainties associated with technological, geological, social and environmental aspects in the long term. Examples of these are the risk of low productivity in low-grade ore recovery, unfeasibility of some mining projects due to the lack of social or environmental license, and the difficulty of replacing some metals with special properties [41,112,113]. Nevertheless, both paradigms can be reconciled, that is, it is possible to deal with the exhaustion of mineral resources, but without sacrificing the future use of resources that are geologically scarce [112]. As such, the internalization of the environmental and social costs in the mineral production from institutional initiatives becomes critical [110,113].

Although several minerals are relatively abundant, there is a global concern regarding the shortage of some particular resources. This is the case, for instance, of some alloy elements such as nickel, titanium, cerium, lanthanum, and tellurium [6]; elements progressively demanded in the development of renewable energy technologies such as tellurium, indium, dysprosium, neodymium, gallium, chromium, cobalt, silicon, and cadmium; electric transmission lines such as copper, silver and other non-magnetic metals; and storage batteries such as zinc, nickel, cadmium, and lithium [8,91,106]. Some of these elements are considered “critical”, not necessarily due to their geological scarcity,

but due to multiple potential supply risks [13,108]. One example is copper, whose relative abundance contrasts with the supply risks associated to the high demand for it, the difficulty in replacing it, the progressive drop in run-of-mine ore grades in a global scale, and to the geopolitical and climate change risks [4,92,95]. Another example is uranium, a potential alternative energy source, whose use, however, is restricted due to social concerns regarding the environmental and safety risks, besides political restrictions, as well as historical opposition to its extraction by indigenous people which occupy part of the land where some deposits are found [13,114]. Geopolitical supply risks of mineral resources have been recurrent over the last decades for certain commodities: cobalt in the 1970s, palladium in the 1990s, and rare earth elements (REE) in recent years. In this regard, the recent dominant role of China as the largest supplier of REE—which are in high demand for several *high-tech* applications—is notable [108,109,115]. Indeed, the country is the primary mining producer of 34 metals, 23 of which are considered “critical” by the European Commission [115].

In general, the perception of scarcity may be more associated to the time [4] and the large investment that new extractive operations demand [6], as well as to the management of impacts associated to the exploitation and use of minerals [8], rather than to the actual availability of mineral deposits. Indeed, a significant part of the mineral resources has not yet been explored for geopolitical and economic reasons, as well as due to geographic inaccessibility. In fact, the exploration has been mainly focused on high-grade deposits, through which it has been argued that there is not a realistic estimate of the proportion of metals that can be effectively extracted from the Earth’s crust. Three types of scarcities of mineral resources have been reported [116]:

1. absolute, related to the geological aspects;
2. temporary, when the supply is smaller than the demand; and
3. structural, when some metals are coproduced (“companion metals”) along the production chain of other metals (“carrier metals”) and their supply do not necessarily respond to market demand.

Several methods have been proposed with the purpose of estimating the criticality of metals. A recent example is the work of Henckens et al. [116], which is based in the concept of geological scarcity, defined as the number of years that are left before the extractable resource becomes exhausted. This is calculated based on the mass of extractable resources—according to UNEP International Resources Panel Framework—and the rate of annual extraction in t/year. With this approach [116], the authors concluded that the exploitation of selected metals—Sb, Au, Mo, Re, Zn, Ag, As, B, Bi, Cd, Cr, Cu, Fe, Ni, Pb, Sn, and W—is unsustainable in a pre-established 1000-year timescale. However, recent critiques to this type of approaches have been pointed out [109], since the geological scarcity is based on the life expectancies of mineral commodities that involve estimates of future resource consumption and available stocks which, instead of “fixed”, are sensitive to change over time. Another recent example is the study of Graedel et al. [108], where a robust methodology to evaluate the criticality of 62 metals at moderate to longer timescales (5–50 years) has been proposed on the basis of a 3D criticality matrix, which has been built upon previous work [107]. The authors concluded that the most critical metals at global scale include those characterized by their availability as “companion metals” as well as by their use in modern electronics and in thin-film solar cell technology such as In, As, Tl, Sb, Ag, and Se; those that imply potentially higher environmental impacts (per kilogram of metallic element at the factory gate, from a LCA perspective), including precious metals such as Au and PGMs; and those that are not replaceable, such as Mg, Cr, Mn, Rh, Y, and various REEs. Thus, these elements should be prioritized and optimized in their use, even though a large uncertainty has been recognized in this analysis due to limitations in the data available and to the dynamic nature of the metal criticality assessment.

6.2.2. Resource Use Efficiency and Secondary Resources

A more sustainable use of mineral resources is possible, as the environmental and social costs of extraction of minerals are compensated and that satisfy all stakeholders. It is also necessary to

put an effort in increasing the durability of products, dematerializing products and services while maintaining their functionality, replacing potentially critical materials, and closing the life cycle of materials—*cradle-to-cradle*, circular economy—through an increase in the rates of recycling and reuse [7,116]. The concept of dematerialization can help establishing a priority in relation to which services can be provided with a lower demand of materials in long-term, although this may not be enough to support the sustainability in the exploitation of mineral resources [8]. On the other hand, the replacement of alternative materials should consider the supply of a material in a long-term horizon, through which a change to a material that is equally critical and non-renewable may not be a good choice, particularly if this alternative material is being sought for multiple replacement options [13]. Indeed, this replacement must also consider the potential impacts that are being generated (and avoided), aiming at a comparison between the traditional and the alternative material along their life cycle, on the basis of the same functional unit.

From a theoretical standpoint, metals can be recycled and recovered from wastes due to their physical nature [6,41], since metallic bonding is unaffected by melting [117]. Operating costs in recycling, associated to collection, transport, dismantling, classification, and refinement, are initially high. However, these costs can be potentially reduced in the future due to the increase in the prices of mineral resources [116], the technological advances, the increase in the production scale and rates of recovery, as well as due to the greater public and private funding in regulating the market of secondary resources. For the particular case of metals, the final price of a metal product is influenced by its usefulness for a particular application, and the content of recycled material in it depends, among other things, on the availability of the secondary material—with a quality similar to the conformity criteria demanded for the primary material—in the manufacturing process [117]. The complexity of wastes and their recycling and recovery potential are variable. There are, for instance, well-established recycling practices in some metallurgical sectors such as the production of steel and aluminum [61,91], where huge gains in energy efficiency are achieved. Furthermore, in these cases, the collection and recovery may have become profitable in terms of scale by the larger amount of metal recovered per unit of discarded product, for instance in the recycling of scrap and packaging.

Nevertheless, other metals—rare earth elements, vanadium, and zirconium—are harder to recover, thus their rates of recycling are extremely low. Recycling, therefore, becomes more complex when the elements are present in low concentrations in the various products available in the market [91], although a growing demand for some metals could make their recovery economically feasible. Therefore, some stocks of discarded products containing metals could be potentially considered as future additional mineral resources [41]. However, there are still challenges in the wastes generated by some metallurgical processes. Two examples are red mud, a residue generated in the extraction of bauxite by the Bayer process, and zinc ferrite, a residue from roasting zinc sulfides [6]. Metal recovery in wastewater is even more challenging because the technologies necessary to capture these metals in large volumes of water require very high selectivity, which is not reached in conventional separation processes, for which it is more recommended to use sorption processes [40].

Waste sorting is a critical factor for the recycling of wastes in general, and must be conducted with the aim of minimizing inefficiencies along the process—energy demands, waste transport, etc.—for which it is relevant to consider the system from a more holistic standpoint in comparison to possible alternatives of recycling and reuse for a given material [13]. Indeed, recycling, in analogy to mining, can be either properly or poorly conducted and, therefore, generate risks and negative impacts, such as the case of health and well-being issues associated to informal recycling by workers in Asia [57]. Finally, to better quantify the impacts associated to recycling, it has been pointed out [117] that it is more appropriate to use the “end-of-life” or LCT based approach, rather than the “recycled content” approach.

6.3. Human and Social Well-Being

Sustainability in the supply and demand of mineral goods is becoming progressively more relevant from the geopolitical standpoint. The difficulty in finding high-quality mineable resources in strong mining economies is leading to several new exploitation projects in developing countries [13] and regions with poor governance. In some cases, this can be associated with lack of standard practices and with small-scale operations, which may often lead to the application of poor technologies and weak safety protocols, resulting in safety and health risks for workers [3,62]. In general, however, technological advances and increased demand for mineral resources lead to a growing scale of the exploitation and processing of minerals, which implies the adoption of high safety standards at organizational level—organization of workspaces, training of workers, and development of a culture of safety—to avoid fatalities and reduce occupational health risks to workers [1,3].

Underground mining, in particular, is related to a high rate of accidents, which often involve catastrophic consequences. In coal mining, there are, for instance, several natural risks which must be monitored and managed continuously—through physical and geophysical measurements, mine planning, appropriate technologies—in order to minimize them [1]. Guaranteeing health and safety in the operations is, therefore, a key social responsibility of the mining companies with its workers, although not the only one. There are other corporate social responsibilities that are being, or at least should be, included in a wider scope: vocational development, work stability, proper wages, good living conditions for workers and their families, career development, right to form labor unions, more participation of women in the labor force and equal pay, among others [1,2,49].

There is yet another level of social responsibility of the mining companies on a larger scale, which involves the relationship with the local communities, which is key in acquiring and maintaining the social license to operate. This concept has emerged in the minerals industry—having been extended, for instance, to the energy sector—as a key matter that is oriented by the community, in terms of an informal extension of the traditional licensing of a mine, which implies approval by the communities. In mining, there is often a bias towards opposing locally to a new project, but in the case of particular mineral-energy projects such as the production of nuclear power, the coal exploitation, and the hydraulic fracturing, such opposition has reached the sector as a whole [57]. It is now recognized that the relationship with the local communities must be, therefore, continuously encouraged through a participative process, where the social impacts are considered from the initial stages of the mining project—including the design stage, where technical and economic aspects have been dealt with—up to the end of the life cycle of the mine. As such, the aim must be to increase or, at least, preserve the well-being of the population and reduce any possibility of conflict or long-term prejudice [43,47,56]. It is important to acknowledge that these communities are the ones that will use the land after the extractive activity is finalized so that they have an important role in the decision-making process [47], even if the law does not require that. As such, it is also important to respect the cultural circumstances of indigenous people in the decision-making process with respect to the consent to develop mining activities in an indigenous land [49].

The well-being of local communities is directly related to the preservation of the natural environment where the extractive activity is carried out, but also to the economic benefits that can arise from this activity in the regional context. Therefore, the mineral sector has an important role in the generation of both direct and indirect jobs, helping to stimulate hiring local personnel and create other employment opportunities after closure of the operation. The mineral sector can also contribute supporting regional services such as health, education, well-being, infrastructure—roads, rails, water and electricity supply—and funds for regional development projects [7,43]. Another relevant matter in relation to the development of the communities that are directly involved with the extractive activities is the social responsibility of the governmental sector in terms of regional planning, aiming at satisfying the needs of these communities during and after the development of a mining project [57]. The unsuitable or inexistent governance in regions where natural resources abound can lead to social conflicts of varying intensity. A particularly dramatic example is the extraction of diamonds in

Sierra Leone, in which corruption practices are strongly embedded [80]. Indeed, there are peculiarities in the mineral sector that, added to an unsuitable governance, can increase the risk of corruption: a large amount of capital involved, extensive requirements from regulation, and development of activities in well-defined locations [49].

The negative perception from some sectors in society in respect to mining is, unfortunately, justified in several cases, but it has also been potentialized by the wide media, in particular, associated to coverage of disasters caused by these activities. On the other hand, successful mining projects do not get much visibility. In contrast to that, other industrial sectors also connected to the extractive activities have been able to improve their corporate image [91], for instance in relation to improvements in reduction of their footprints. Unlike the manufacturing sector, where producers can build a more direct relationship with customers, the mining industry hardly has this possibility given its initial position in multiple productive chains to which it is related. This demonstrates the need for the mineral sector to place additional effort and seek strategies that will help overcome this negative global perception of its operations, towards contributing to change the current unsustainable trends of production and consumption [8]. Besides that, it is necessary to increase the commitment from other industrial sectors as well as from society, given that increased consumption does not imply a better quality of life [7].

6.4. Economic Prosperity

6.4.1. Mining, Economic Growth and Well-Being

It is estimated that the extraction of natural resources contributes directly or indirectly in more than 45% of the global GDP [47]. However, this activity has also been causing a series of social and environmental impacts that must be avoided in the future, changing the business-as-usual development model. It has been recognized that it is key that the emerging economies do not continue the same inefficient and destructive trajectory that followed countries with more evolved economies to reach this status [13]. This is particularly important since some emerging economies located in less developed regions of Africa and South America are becoming progressively more dependent on the export of mineral resources [7]. In theory, the commercialization of mineral resources can generate important revenue for these regions, helping to reduce the levels of poverty and inequality. However, there are factors such as corruption and government decisions that can hinder these potential investments. Indeed, these investments may even be reduced, for instance by the application of state policies that aim to diminish royalties and taxes to the mining companies, which, according to some authors [65,80], has been occurring under the recommendation of some programs supported by institutions such as the World Bank.

The large geographic imbalance in the distribution of mineral resources is evident, both in respect to access to these resources and to the implementation of policies associated to its exploitation. It is recognized, for instance, that a deficit exists in the access to electricity by a significant part of the population from parts of Latin America, Sub-Saharan Africa, China, and India, among others [1]. In contrast to that, a positive correlation has been reported between the exploitation of mineral resources and the economic growth in some countries such as Chile, Indonesia, Botswana, China and India, being the last two the greatest responsible for the significant increase in the rate of exploitation of minerals that started in the 1980s [1,80].

An important characteristic of several emerging economies is the tendency to export raw materials to the developed countries—in contrast to final products, for instance, *high-tech* products—in a globalized economic scheme where the greatest part of the production is concentrated in multinational companies, whose production is in large scale. The capital expenditure involved in mining projects is typically very large, and the number of people that are directly dependent on these projects could be around approximately 250 and 300 million [2], although the number of jobs created is small [65] when compared to the amount of revenue generated. On the other hand, when commodity prices fall, mining companies usually respond by reducing their operating costs and improving their efficiency, but this may also represent laying off workers and putting stops on new hires, and even in some cases implying the migration of workers to ASM [60]. However, it is important to emphasize

that extractive activities also generate a significant number of indirect jobs associated to the productive chain [2], including the production, use, reuse and recycling of metals and manufactured products that use these metals, besides other non-metallic mineral resources that are also used in several other industrial sectors. Nevertheless, a significant fraction of these jobs is available where the mineral resources are transformed and recovered, which does not necessarily occur in developing countries.

Unfortunately, the economies of countries that are highly dependent on the export of raw mineral resources can become very fragile and such exports do not always lead to economic growth. On the one hand, the international price of commodities has been more volatile—particularly over the short run for important metals [109]—than that of the manufactured goods [80]. On the other hand, the final products tend to be more highly valued in the market than raw materials. In industrial scale, it is also observed that mining companies are more affected economically by the fluctuation of global ore prices, while industries that transform raw materials are less susceptible to these variations [91]. The prices of commodities are generally determined by the relationship between supply and demand, which tends to vary constantly, while the production tends to be more stable and predictable. When resources tend to become exhausted—temporarily and not physically—or when production costs increase significantly, there is an attempt to take charge of controlling the prices. However, if exploration activities are intensified then the supply increases with respect to demand, and the prices of commodities tend to further drop [118].

Economic growth by itself is not necessarily coincident with human well-being [80], neither with sustainable development. Indeed, this well-being does not reflect in economic indicators commonly used such as the Gross Domestic Product (GDP). In respect to the economic dimension, it is argued [86] that this indicator disregards the extent to which the stock of capital of a nation changes as the result of its current production. Indeed, the GDP does not include the depreciation of physical capital, in contrast to the Net Domestic Product (NDP), through which Eggert [86] recommended that this latter one would be more appropriate in terms of quantifying economic sustainability, in spite of disregarding the other aspects of sustainability. A “green NDP” has also been proposed with the aim of including some environmental aspects, but this indicator still does not consider social questions associated with sustainability. However, despite the efforts, the green NDP has not yet been able to replace the traditional GDP as an indicator of well-being [86]. There is no shortage, however, of indices that consider some special social and environmental questions. Examples are the Human Development Index (HDI) and the Genuine Progress Indicator (GPI) [106].

6.4.2. Development of Primary and Secondary Resources

While several developing countries became progressively more dependent on exports of mineral resources [2,7], some more developed economies are forced progressively to change their energy matrix due to the growing dependence on imports of fossil fuels and the environmental implications of their use. This is a potential energy security problem for these countries, which becomes even more relevant from the standpoint of strategic mineral resources for the development of clean technologies [1]. The continuous global population growth coupled to the current standards of production and consumption make the availability of energetic and non-energetic mineral resources critical.

Indeed, it has been argued that in the transition to a more sustainable economy there may be a risk of supply of mineral resources in the future decades. On the one hand, the rates of recycling of several metals remain low and, on the other hand, the minerals industry could have challenges in supplying the demand for some metals that remain unreplaceable [4]. This last aspect is related to the life cycle of the mining project, where the initial stages since discovery of a mineral deposit until the start of the operation, can take several years, being subjected to several short-term risks (commercial fluctuations, financing issues, unpredictable technical problems, legislation changes, social challenges) which can affect the feasibility of a mining project in the longer term [91]. For copper ore, for instance, the time between discovery and development of a mineral deposit usually takes between 13 and 23 years [4]. When this is combined with the need to guarantee acceptable environmental and social conditions,

as well as with the risks of a potential water shortage associated with the effects of climate change [92], the mineral sector can face progressively greater challenges to develop new deposits which allow dealing with the drop in production [4]. All these factors may be influencing the preference of the mineral sector in extracting lower grade resources and investing in brownfield projects rather than in developing new (greenfield) deposits [118].

The technical and economic potential of the extraction of a mineral deposit is based on several pieces of information, that include tonnage, ore grade, depth, location and economic feasibility [47,116], up to a preselected cut-off grade. As such, additional mineral reserves may be established during operation of the mine [86]. Historically, the market has decided on investing or not in the exploration of mineral resources according to short-term returns [4]. Indeed, production and demand forecasts of mineral goods are also based on short-term (5–10 years) scenarios, and focus exclusively on primary resources, giving little attention to the stocks of secondary resources. While the collection of the information necessary for the annual estimates of primary resources is funded by governments, the collection of information on secondary resources is both less frequent and standardized and is usually conducted by industries and the academia, which does not guarantee the continuity of that information in time. Nevertheless, a number of longer-term scenarios of mineral production are being considered at a research level, taking into account recycling, but mainly focusing on specific commodities and also disregarding the connection between the life cycle of the different mineral resources [57].

The projection of long-term production scenarios for the mineral sector can be very complex due to the high variability of the ore characteristics, and also owing to the nature of the resource estimates based on supply. In contrast, the energy sector has been strongly funded by governments and international agencies for the projection of long-term production scenarios based on possible future demands, which may have been influenced by the central role of energy security in the socio-economic well-being of a nation [57]. It is, therefore, recognized that a more realistic and comprehensive planning of the global production of both primary and secondary mineral resources in the long term is necessary, considering the potential future shortage of resources, in spite of the progressive growth in recycling rates [4]. As such, it is the opinion of the authors that the mineral sector could lead initiatives aimed at investing more proactively in improving the sustainability of its operations through the recovery of secondary resources, particularly those directly generated within their system boundaries. This may contribute to closing the life cycle of the minerals, which would certainly benefit both the regional and global sustainability of the mineral resources. An important work that must be carried out in this sense is the investment in research for the “exploration” and potential recovery routes for these secondary resources.

6.4.3. Operating (Eco)-Efficiently

In the operational context, the efficient management of resources and risks can help improve productivity [48] as well as the economic efficiency of a mining and processing operation. This last one may be understood as a problem of optimization that aims at maximizing the profits of the mining activity [86]. The productivity of a mining and processing operation, on the other hand, can be improved by incorporating the best available technologies, increasing the level of mechanization, ensuring optimum utilization of equipment, properly managing inventories and reducing accident rates [119]. However, increasing productivity alone does not lead to sustainability, which requires incorporating other concepts such as eco-efficiency that aim at minimizing environmental impacts, besides maximizing profits. Fortunately, synergies may be found between these two components, that is, environmental and economic [20]. For instance, reduction in consumption of water, energy, and consumables in the operation can also lead to a reduction in operating costs.

After a period of high growth in both the economy and level of investment, which led to the minerals industry raising production and increasing efforts in exploration, the sector presently faces a challenge of reducing costs and improving the efficiency of its operations while it has to manage to

extract ores with progressively lower grades. This is why it has been recognized that the sector needs drastic changes to guarantee a sustainable production in terms of productivity. An initiative in this direction is the establishment, in 2010, of the Cooperative Research Centre for Optimising Resource Extraction (CRC ORE), with the aim of dealing with the issues of productivity of the extractive industries, through innovative solutions and using an integrated approach in the context of the productive chain [120].

6.4.4. The True Value of the Resource in the Market

In regard to quantifying the investments and capital gains in the mineral sector to determine the financial feasibility of a new project, two common methods are used: the Net Present Value (NPV) and the Internal Rate of Return (IRR). These are based on the reduction in the future cash flow using a single factor (Risk Adjusted Discount Rate), which grows exponentially with time [121,122]. However, methods based on NPV have produced high variability in the valuation of mines, comparable to that of prices of commodities. Despite this and other limitations, the NPV method has been the most commonly used in the mineral sector [121]. Considering these restrictions, the Decoupled Net Present Value (DNPV) has been recently proposed, which splits the risk from the time value of money, allowing to better estimate the real costs of mineral extraction, while maintaining a level of simplicity. Indeed, with this new method, it is possible to account for other types of risks that are not associated to the market—for instance, climate change—in the valuation of a particular mineral resource [121].

The DNPV has also been presented as a robust method to account for potential risks involved in the final stages of the life cycle of a mine: reclamation and post-reclamation. These costs are often artificially reduced, resulting in insufficient funding of these stages, when more traditional cost evaluation methods are used [46]. This could be a useful way to internalize other costs related to the mining project, in a wider scope which considers the life cycle of a mine. As such, the development of more sustainable practices for the sector in a global scale and at long-term becomes possible. Nevertheless, there must be an appropriate planning so that the revenue accumulated along the mine operation period be large enough to guarantee the funding of post-closure activities [46] when revenue no longer comes from resource extraction. The environmental and social costs may also be internalized, for instance, through the carbon trading schemes for the case of emissions of greenhouse gases [6], and through certification schemes which can help incorporate more responsible practices in the sector [48].

6.4.5. Sustainable Consumption and Production

The stock market, and the social and economic systems are characterized by their complex dynamics, as well as by the interactions that exist among their components and with the external environment in different scales of time and geographic location. Therefore, any forecast related to these systems—population or economic growth, and mineral deposit reserves—becomes highly uncertain. The only certainty that exists is that, at some point, a continuous exponential growth of the population will no longer be possible, as well as the use of resources in a planet with physical restrictions. Therefore, the reduction in consumption of non-essential goods and services towards a healthier and happier life could also be considered a strategy to increase the quality of life of a population [106]. However, reducing drastically the consumption of mineral resources and energy becomes difficult due to the strong correlation between the GDP and other variables related to the human development, which have been incorporated in other indices that are farther reaching than GDP. For instance, the global GPI per capita reached a peak in 1978, at the same time there was a peak in the use of oil, exactly when the ecological footprint crossed the global biocapacity [106]. One of the SDGs of the UN is the decoupling between economic growth and environmental degradation. However, the majority of the countries presents a “*weak decoupling*” or an “*intensified coupling*” between these factors [123]. Indeed, social well-being is strongly connected to economic growth. As such, it is key to make economic activities based on primary mineral resources more efficient, but it is also

important to lead the path to the intensified development of other types of markets based on the use of secondary resources. In this way, it would be possible to maintain a balance between global supply and demand of goods and services and, as such, create environmental and social benefits.

6.5. Public and Private Institutional Leadership

The key role of governmental and corporate governance in increasing the likelihood of success in mining projects has been progressively recognized in different geographical scales [13]. This governance can be materialized in the form of policies, innovations, guidelines, standards, and codes of practice, which allow implementing regulations to mining companies in terms of improving environmental and social benefits [11,13]. A proper governance can also help to encourage investment in the diversification of economic activities in countries highly dependent on exports of mineral resources [86]. It has been recently identified the need to pay more attention to how mining is related to governance and empowerment, especially in local and regional contexts [80].

The development of a mineral deposit depends on a series of factors that are defined by public institutions, governments and by the regional and national policies. There are some institutional matters that are specific for the development of a new mining project, such as laws and regulations on the property of mineral resources, access to land, guarantee of continuity, tax regulations, and environmental policies for closure and rehabilitation of degraded areas [86]. In developed countries and regions that are exporters of mineral resources such as the United States, the European Union and Australia, strict laws and environmental regulations started being implemented since the 1970s [3], as soon as the environmental agenda started to become critical at the global scale. In these regulations, it has been common to find the focus on the life cycle of the mine—in special tailings management—the involvement of society along the environmental licensing process, the adoption of risk prevention measures, as well as a rigorous management of environmental issues by competent government authorities, such as the Environmental Protection Agency (EPA) in the United States [3].

In spite of the strict environmental controls in developed countries, some legal violations and increasing environmental impacts from some mines in the United States and Canada, respectively, have also been reported, which may be mainly associated to changing regulations and to the increasing scale and number of operations [20], besides the decreasing ore grades. Furthermore, the restrictions on land use and the environmental regulations in developed countries may be other factors that have led to the greater focus of various extractive activities in developing countries [61], where there are not as clear “rules of the game” in several cases [20]. That is, there is an absence or failure in state environmental policies that can be applied and monitored in the long term, regardless of the ideology of the ruling government, and this can be a strong catalyst for potential conflicts between government, mining companies, and local communities. Moreover, the existence of some environmental regulations in developing countries does not guarantee greater environmental responsibility of the mining companies in these territories [61]. In some South American countries, there are regulations for mining (Mining Codes, environmental laws, etc.) that still have room for improvement in critical aspects such as social impact assessment, public participation mechanisms, greater focus on prevention rather than restoration, and integration of sustainability in legal frameworks throughout the full mining life cycle [63]. In the end, this makes the development of mining projects unfeasible, which may be critical for certain mineral resources such as copper, in which at least one-quarter of the known global reserves are found in countries with poor governance [4]. International and non-governmental organizations could help support the licensing process, some of which have developed guidelines, such as the World Bank and the ICM [86]. These established good practices may be useful, but must be seen only as complementary. It is now evident that a country that aspires to base part of its economy in mining must clearly define a specific political agenda for this sector, which is focused on all aspects of sustainability.

Artisanal and small-scale mining (ASM) activities, on the other hand, have been discursively embedded in a generalized negative context characterized by low mechanization, high labor intensity, low safety standards, poor technical expertise, high inefficiency, high environmental impacts, strong

correlation with poverty, among others [62,72,74], which is not always the rule—as observed in some regions of Ghana and Tanzania, for example [72,124]. The high informality of these operations is a critical factor that can undermine their sustainability, particularly in developing regions such as sub-Saharan Africa [74,125] where 20 million people are employed directly [72,74]. As such, governments play a key role for the legalization of ASM, aiming at the incorporation of the best practices for sustainability, ensuring fair prices, encouraging the development of higher value-added products, and continuously empowering these operations in order to comply with an appropriate regulatory framework [62], and without creating further barriers [74,75,125]. However, standardizing such framework is challenging, especially in developing countries where natural (and mineral) resources—as well as other sustainability concerns in the context of mining, such as economic and social dimensions—have not been properly managed through policy instruments. Further, the dynamics, potential vulnerabilities, ancestral practices, contribution to economic development and to poverty reduction, socio-technological heterogeneity, among other factors, need to be well understood for ASM in differentiated local and socio-cultural contexts [72,74,75,124]. Therefore, ASM formalization should be, according to some authors [74,75,125], a flexible, empowering, inclusive, and context-sensitive process, rather than an ultimate goal or a rigid top-down approach—the latter proven to be disruptive in some cases [75,126]. Initiatives by the UN and the World Bank have given progressively greater interest to the formalization of ASM, but criticisms to these have emerged [72,74].

In a more general sense, there are institutional initiatives oriented to SD in the mineral sector, but with a short-term vision that is mostly restricted to primary resources, with a few exceptions. For instance, the role of governments in countries such as Japan and Switzerland—both developed and consumers of mineral resources—in inducing actions towards specialization in the recovery and processing of secondary resources can be highlighted, and might result in their leading roles in the production of secondary materials in the future [57]. In this regard, it is also noteworthy the role of some companies that have changed their corporate vision towards sustainability, such as the case of Boliden Mineral AB in Sweden [127]. Some political initiatives have appeared, which are focused on the security in the supply of metals and mineral resources, especially in the United States and Europe. As such, lists have been proposed with critical mineral resources, in the sense that their supply restriction may generate risks in the economy of these countries [4,128]. The role of the International Resource Panel (IRP) and of the Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development (IGF) has been highlighted in regard to the compilation of global data on the availability and governance of primary mineral resources, although it has received little attention the formulation of policies related to the exhaustion of resources. Other international organizations with no political power have gathered specialists from different areas to discuss the “science” of resource scarcity, such as the ICMM, which has worked on several social and environmental issues related to the supply of mineral resources. However, the corporate leadership of mining companies towards the management of secondary mineral resources is still limited, although some refineries controlled by mining companies process both primary and secondary materials [4].

With the aim of making management of mineral resources more sustainable in a global scale, it has been recently proposed [112] to establish an international agreement that is focused on geologically scarce mineral resources, in a way that is similar to how it has been carried out in other global environmental concerns such as biodiversity and climate change. The main objectives of this agreement would be [112]:

- Choice of the minerals that must be prioritized in terms of reduction of extraction rate;
- Definition of sustainable extraction rates, introducing the reduction necessary in the exploitation of each mineral resource and the period within which those reductions are to be achieved; and
- Allocation of an exploitation limit for priority resources between producing countries—as well as those potential producers—of these minerals.

Certainly, one of the main challenges to reach this international agreement in the sustainable use of scarce mineral resources is the proper definition and quantification of which of these are really critical, considering the multiple risks of future economic and technological disruptions at national and global scales [108]. In this way, it has been suggested the use of a classification that takes into account a series of criteria for a more holistic analysis, such as: the geological scarcity; the value, functionality, and service of the mineral resources to society; the recycling or substitution potential of a particular material or chemical element; the supply risks associated with geopolitical, social and environmental issues, among others [8,108,112,128]. An international scheme for periodical assessment of the criticality of extractable resources is also desired for that purpose [112].

It has also been proposed [4] to consolidate a partnership between the IRP and the IGF, with the aim of improving governmental planning of mineral resources on a global and long-term scale, based in existing treaties, and incorporating ecological restrictions through the recently created United Nations Environment Assembly (UNEA), an international organization with political power in respect to the environment. Indeed, it is proposed [4] to deal with priority matters such as: establishing international goals for the global mineral production; monitoring the life cycle impacts in the production and consumption related to mineral resources; stimulating greater collaboration between government and the industries in terms of improving research and technological innovation for the mineral exploration in a planetary scale—given the technological, economic and governance uncertainties for “lunar and asteroid mining”; adopting the best practices for responsible mining at global scale; and creating inventories to establish the availability of secondary mineral resources.

In conclusion, a good strategy for governance from a local to a global scale could be the path towards the sustainability of mineral resources. This would be possible as the governments of mineral resource exporting countries—especially those in developing countries—could establish proper policies for the sustainable management of both primary and secondary mineral resources within their jurisdictions. This strategy could also be incorporated into the corporate vision of the extractive industries worldwide, with the aim of improving the performance of their operations along the life cycle of a mine and its derived products. This can be realized by adopting best practices and available technologies, and also supporting the improvement of extractive operations, aiming at the development of projects and markets based on the use of secondary resources in a collaborative scheme that involves other industrial sectors, consumers, and stakeholders, such as in the Global Production Network (GPN) approach [60,129].

6.6. Sustainability-Driven Technological Innovation

Technological innovation is key for sustainable human development. Along the last centuries, there have been a series of radical technological innovations which have been associated with the different economic cycles. This theory has been supported from a neo-Schumpeterian perspective, rooted in Kondratiev’s work concerning the cyclic phenomena in the modern world economy [130–132]. Thus, each “Kondratiev cycle” has emerged as a new paradigm in relation to a scenario of economic crisis. In that sense, innovation and wide diffusion of technology have relied on prior development in different areas, and have led the way to new cycles of technological innovation. Technological waves started with the industrial revolution, until the more recent information and telecommunication wave [130,131]. It has even been argued [132] (p. 29) that the “Life Cycle of a Technological Revolution” can last for about half a century. Therefore, the recent economic crises from 2007–2010 could be interpreted, as suggested by Morone [131], as a possible sign of the end of an economic cycle and the beginning of a new wave based on more sustainable modes of production and consumption, led by the resource use efficiency, the use of cleaner technologies, and the valorization of wastes. In that sense, a series of technological, social and institutional changes occurring simultaneously and focused on the same goal are required [131].

The mineral sector became innovative particularly from the beginning of the 20th century [54,133,134], with the rapid expansion of electricity as a power source by industry. This led to the development of

large-scale machinery—first reducing, then eliminating human muscle—and to the improvement of wear and impact resistance of the materials used in these artifacts and in working tools. Further, mineral resource extraction for use in technologies accelerated particularly since the second half of the 20th century [108]. However, this also implied increasing impacts on soil, air, and water [135], as well as in the communities located nearby. As such, the availability per se of technological advances does not guarantee that they will be adopted responsibly by the mining industry. For instance, the case of the Ok Tedi mine is worth mentioning, in which BHP Billiton opted for discharging tailings directly on the local river, given the difficulty involved in building a tailings dam in such unstable and high precipitation area, that resulted in a series of further legal actions. Another example is the submarine disposal of tailings, a little-tested technology that has been related to environmental problems, being expanded in some developing countries, despite opposition by members from society [65].

On the other hand, it has been argued that most of these innovations have come from outside of the mining industry, either through transformation industries, suppliers or equipment manufacturers [7,133]. Indeed, the main focus of these innovations has been to increase the techno-economic feasibility of operations [86]. It has also been established that this industrial sector tends to be perceived as conservative [134] and averse to risk [7]. In fact, there is a tendency to protect the competitive advantage in relation to technological solutions offered by suppliers, which becomes a limitation for publicizing the best technologies and practices in the industry. However, some partnerships have been created between mining companies, governments, and research institutions. An example is the AMIRA International initiative, which has allowed fostering innovation at R&D level in the sector [7]. The need to innovate derives, on one side, from the environmental and social responsibility of mining companies along the life cycle of its projects [1]. On the other hand, this need is connected to the intrinsic uncertainty of the geological materials, and also to the various sources of variability—deposit and ore characteristics, bulk properties, logistics, customer's needs, commodity prices, etc.—along with the productive chain [134].

The multiple factors and stakeholders involved in the development of mining activities require adopting innovations in the minerals industry, with the aim of making both present and future operations globally sustainable. As the easily mineable resources become scarce and head grades drop, more complex concentration methods are needed. This is where technological innovation becomes a requirement to make operations more sustainable, so that the real production costs become competitive in the market, the mining waste is reduced, and the resource use efficiency as well as the recovery of the valuable minerals increase, besides reductions in costs and impacts of infrastructure and transport are achieved. Indeed, whereas the supply and demand determine the commodity prices in the short term, technological innovation and its rate of incorporation in operations are key to support the stabilization or even reduction of commodity prices in the long term [54].

The relatively limited volume of funding for research and development in the minerals industry, when compared to other industrial sectors, does not render it a label of a *high-tech* industry, in which information technologies are highly incorporated [133]. As such, this is an important path that could be followed in the upcoming years in terms of innovation in the minerals industry: integrating the use of eco-efficient technology with information systems in the production processes, considering the multiple sources of uncertainty, as well as the factors that are either directly or indirectly associated to the mining industry. Several of such advances that can contribute to sustainability have been summarized (Table 2), besides several other technological innovations, which, although not so recent, have not yet fully incorporated in mining and processing of particular commodities and in some developing countries.

Table 2. Examples of technical and technological innovations in the minerals industry. Adapted from: [20,54,57,133,135].

20th Century	Emerging Technologies (21st Century)
<i>Comminution and classification equipment</i>	
- 1900–1928: Rod mills; multiple-chamber tumbling mills; vertical roller mills (VRM); inclined classifier; autogenous pebble mills - 1930–1959: Cone crusher (Symons); vibrating ball mills; primary autogenous mills (rock or ore as grinding media); hydrocyclones - 1960–1980: High diameter /length ratio semi-autogenous mills; vertical shaft impact crushers (VSI); optimized-design VRM; centrifugal mill; high-pressure grinding rolls (HPGR); high-efficiency air classifier (second and third generation); - 1985–1999: Large diameter roller and tumbling mills; higher capacity tower mills (above 1000 t/h fine grinding)	<i>Process innovations</i> - Dry separation at coarser sizes (significantly reduce the mass of material required in grinding, handling and concentration) - Use of dry sand fluidized beds as density separators for lump ore (10–50 mm), aiming at reducing the water consumption, or early rejection of coarse gangue (reduction of energy consumption and GHG emissions)
<i>Grade control</i>	
- Kriging - Computational modeling and simulation	<i>Location and mapping of resources</i> - 3D mapping
<i>Surface mining</i>	
- Opencast mining - Semi-mobile crushers	<i>Recovery from end of life goods</i> - Batteries; printed circuits; automobiles
<i>Underground mining</i>	
- Ammonium nitrate-based explosives - Carbide and electrical lamps - Rock bolting	<i>New extraction methods</i> - Oil shale and shale gas; phytomining; bio-leaching; in-situ leaching; super block-caving, deep-sea mining
<i>Production programming</i>	
- Operational research - Truck tracking by GPS	<i>Increase in productivity, scale and safety in extraction</i>
<i>Other innovations</i>	
- Coal: long haul extraction; continuous mining; dragline excavator - Copper: flotation; SX-EW (solvent extraction and electrowinning) - Uranium: in-situ leaching - Gold: heap leaching; autoclaving; cyanidation instead of amalgamation techniques - Nickel: high-pressure acid leaching - Air quality improvement (scrubbers, electrostatic precipitators, baghouses) - AMD abatement technologies - Land rehabilitation techniques - Cleaner Production practices	- Larger scale equipment (bucket wheel excavator, draglines and trucks) - Automation of drilling machines, trucks and trains - New design in mine operation with the aim of improving the optimal operation of automated machines - Larger quantities of remote operation and control centers - More efficient processing routes according to the ore characteristics, on the basis of geometallurgical models

Technological innovation aiming at sustainability can also be incorporated from design. From one side, equipment manufacturers can introduce enhancements not only by reducing costs and improving the functionality of artifacts, but also optimizing the use of the materials through dematerialization, recycling [86] and substitution. On the other hand, there is great potential to incorporate innovations in exploitation and processing operations from the conceptual design stage of the mining project [11,41,45]. As such, concepts of recycling can also be adopted at this level—for rock waste and tailings, and possibly aiming at recovery from industrial and urban wastes, such as Construction and Demolition Wastes (CDW)—to mitigate the environmental impacts at a larger scale and generate additional social benefits [45], on the basis of industrial ecology and circular economy principles [57]. There is also enormous potential for eco-efficiency improvement throughout the operation. In the metal production chain, the initial stages up to the ore concentrate production

represent an important fraction of the total economic costs per unit of metal produced. These stages are characterized by their high inefficiency, both in metal recovery [91], and in resource use.

A recent historical analysis of the annual costs of production for the mineral sector in Canada [66] demonstrated that the contribution of the energy consumption—fuel and electricity—to the overall costs has continuously increased from 5% to 15% between 1961 and 2009 for metal ores, and from 12% to 19% for non-metal ores. Therefore, the issue of energy efficiency is becoming more relevant for the mineral sector in the sustainability context. This study [66] also highlights that the present concerns with the consumption of fossil fuels and its implications in climate change—added also to the minerals–energy nexus and to the concerns related to the drop in ore grades—result in greater justification for improving energy efficiency in operating practice. However, there are still some financial, behavioral and organizational barriers that must be overcome [66]. The authors also identified the difficulty of mines located in remote areas to access the electrical grid, although they also recognize that this might become a driver for seeking improved energy management. For instance, increasing recovery of thermal energy generated by burning fossil fuels. Another energy-related innovation is the incorporation of renewable sources, whose feasibility depends also on local conditions. There are, therefore, important opportunities to improve eco-efficiency of mining operations on the basis of currently available technologies. A list of examples is:

- Integrated mine-to-concentrator optimization [134,136–138];
- Pre-concentration at coarse sizes and Grade Engineering® (CRC ORE, Brisbane, Australia) [134,139];
- Pretreatment for preferential breakage and mineral liberation improvement [134,137];
- Technologies for improving energy efficiency in comminution [134,137,140];
- Advanced design of process circuits towards eco-efficiency and flexibility [134,138,141–143];
- Process automation and control [143,144]; and
- Proactive management of mining waste from early stages along the project life cycle [79,90,93].

As mentioned, it is possible to take advantage of technological innovations to not only improve economic, but also social and environmental aspects of the mining operations. However, the total socioenvironmental benefits that arise are usually challenged by the drop in ore grades and by the increase in total production, in spite of efficiency improvements [8,19]. This is, in part, due to the rebound effects, which are difficult to quantify but must be considered with the aim of reaching the SDGs [19]. On the other hand, technological innovations have allowed processing of increasingly complex ores. Traditionally ores in deposits located close to the surface and with relatively high grades have been processed. With the progressive decline in ore quality, added to the social pressures for the use of land [8], and to the population growth and continuous increase in consumption of goods and services, resources from unconventional sources are being sought, including technologies such as in-situ mining, deep underground mining, deep-sea mining, phytomining and landfill mining [8,53,57]. Each one of these options has potential risks, benefits, and impacts in time that need to be investigated and anticipated. As such, metallurgy and particularly mining has great challenges from the technological standpoint, since it has been traditionally focused on the exploitation and processing of minerals that occur naturally [6–8] and relatively easy to extract.

7. Concluding Remarks

The present review of the literature on the paradigms, views, challenges, and opportunities on the issue of sustainability in the minerals industry context demonstrates that a long path has been walked towards the ultimate goal of a “sustainable society”. However, the mineral sector must continue increasing efforts to make its operations truly sustainable from a more holistic perspective, which considers:

- Proactive management and continuous engagement with the different stakeholders throughout the life cycle of both mining projects and products based on mineral resources, which requires attention on proper management of primary and secondary (recycled) resources;

- Sustainability dimensions beyond the Triple Bottom Line, giving greater emphasis to institutional leadership and sustainability-driven technological innovation;
- Multiple spatial and geographical scales of mining activities from local to global contexts; and
- Intra- and intergenerational equity, aiming at the sustainability of mineral resources in a long-term horizon.

In that sense, it becomes particularly relevant to adopt more systemic and well-established LCT-based approaches, such as LCA (despite its limitations), whose application in minerals industry still needs to be refined.

It is also important to emphasize that the present research is not intended to discourage the publication of sustainability reports by mining companies. Quite the contrary, it is necessary to continue generating this valuable information, but with a greater rigor and transparency, according to the different criticisms raised by several authors hereby mentioned. An improvement in this direction is expected, given the continuous evolution of the standards established by GRI and ICMM. This information is highly useful, not only at the level of sustainable corporate management but also in academic research. This can also be one of the possible ways to communicate effectively with society to make the good practices in mining more visible worldwide.

The sustainability of the minerals industry has been approached here in general, according to recent literature, with a greater focus on large-scale mining. Of course, in the case of artisanal and small-scale mining (ASM)—which has been approached here to some extent but deserves special attention—there may be additional sustainability issues (risks associated with the use of mercury in gold mining, historical land occupation, capacity to internalize environmental and social costs, coexistence with the large mining companies, child labor exploitation, technical skills and access to technology, etc.), but the framework and topics discussed here may also provide a basis for a more detailed analysis of this scale of mining in a broader context.

We hope to have contributed a bit more to this ongoing construction of “wisdom”—as pointed out in the enthusiastic paper of Lehner [127]—based on a historical perspective, but also considering the recent discussions and advances in the science of sustainability related to mineral resources. Finally, we highlight the *Breaking New Ground* report’s contribution—an in-depth content document widely cited by several of the authors mentioned herein—as a “reference book” for all those who develop research in this field. By the way, there is a future!

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