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Responsible Sourcing of Materials Required for a Resource Efficient and Low-carbon Society

Edited by

Lucia Mancini and Philip Nuss

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Special Issue Editors

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Special Issue Editors

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Contents

About the Special Issue Editors

Lucia Mancini works as a scientific officer at the European Commission Joint Research Centre (JRC). On the Raw Materials Team, she supports projects related to social sustainability in the extractive sector and responsible sourcing of minerals. She contributed to the revision of the methodology for the identification of critical raw materials for the EU and to the development of the Raw Materials Scoreboard and the EC Raw Materials Information System. Previously, at JRC, she worked in the development of methods for enhancing the consideration of resources and critical materials in supply chain analysis and in life cycle impact assessment. She is part of the Advisory Board of the UN Life Cycle Initiative project on Social Life Cycle Assessment and of the Advisory Board of the H2020 project RE-SOURCING. Lucia has an academic background in agricultural economics and ecological economics. While obtaining her Ph.D., she was a visiting scientist at Wuppertal Institute for Climate, Environment and Energy (Germany), where she performed a study on food chains' sustainability using material intensity analysis.

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Preface to "Responsible Sourcing of Materials Required for a Resource Efficient and Low-carbon Society"

Our modern economy relies on the quality and availability of natural resources such as, e.g., biotic and abiotic raw materials, water, land and soils, clean air, and biodiversity. Driven by population growth and economic development, future demand for natural resources is expected to further increase in the coming decades. Raw materials including metals, non-metallic minerals, and biomass will be an important part of society's future material mix as countries increasingly transition towards resource-efficient and greenhouse gas neutral economies. These materials are also fundamental to meet ecological and socio-economic targets within the Sustainable Development Agenda of the United Nations. For instance, they have a fundamental role in renewable energy technologies, new building materials and infrastructure, modern communication systems, and low-carbon transportation.

However, some materials are largely supplied from countries with poor governance and the future availability of these materials could be threatened by various factors including, e.g., social and environmental impacts during materials provisioning and production. The raw materials criticality studies developed in recent years have explored amongst others economic, geo-political, and technological factors that could affect the raw materials' security of supply. Environmental and social pressures also play an important role in the materials security of supply and can present obstacles to a future transition to low-carbon societies required for achieving the climate targets under the Paris Agreement. For instance, conflicts can prevent access to mineral deposits; accidents and environmental damages compromise public acceptance and can hinder future extraction operations.

From the industry perspective, companies increasingly evaluate and report environmental and social performance. Responsible sourcing of minerals and supply chain due diligence are sometimes integrated in companies' risk management strategies.

This book presents research papers with a focus on future outlooks of materials supply and use, the consideration of associated environmental and social implications, and issues of raw materials criticality and a circular economy. It highlights the importance of proper data and knowledge with regards to materials availability, materials flows, social and environmental impacts along the supply chain, and how materials supply and demand might evolve in the coming decades.

We are grateful for the well-drafted manuscripts that we have received from leading researchers in the field for our special issue and hope that the compilation of all papers in this book format provides for a concise and interesting overview of currently ongoing research in support of the envisaged transition towards increasingly greenhouse gas neutral societies by 2050.

Lucia Mancini, Philip Nuss

Special Issue Editors

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Editorial

Responsible Materials Management for a Resource-Efficient and Low-Carbon Society †

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† Disclaimer: This scientific output does not imply a policy position of the European Commission. Neither the European Commission nor any person acting on behalf of the Commission is responsible for the use that might be made of this publication. This paper does not necessarily reflect the opinion or the policies of the German Federal Environment Agency.

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Abstract: Our societies rely on the quality and availability of natural resources. Driven by population growth, economic development, and innovation, future demand for natural resources is expected to further increase in coming decades. Raw materials will be an important part of society's future material mix as countries increasingly transition towards resource-efficient and greenhouse-gas neutral economies. Raw materials are also fundamental to meet ecological and socio-economic targets within the UN Sustainable Development Agenda. For instance, they have a fundamental role in renewable energy technologies, new building materials and infrastructure, communication systems, and low-carbon transportation. However, some materials are largely supplied from countries with poor governance. The future availability of these materials and associated impacts are of increasing concern going forward. Recent raw material criticality studies have explored economic, geo-political, and technological factors that affect materials' supply. However, environmental and social pressures also play a role in their security of supply. For instance, conflicts can prevent access to mineral deposits; accidents and environmental damage compromise public acceptance and can hinder future extraction operations. This article will introduce this Special Issue with a focus on material requirements and responsible sourcing of materials for a low-carbon society, and provides an overview of the subsequent research papers.

Keywords: raw materials; environmental and social sustainability; responsible sourcing and resource governance; due diligence; future scenarios; security of supply

1. Introduction

1.1. Raw Material Trends

Raw materials are essential to fulfill many human needs, from the basic ones like shelter, to more specific needs like communication and mobility. The amount [1] and variety [2] of materials used in modern economies drastically increased in the last century to around 90 Gt (billion metric tons) in 2017, causing concerns about the associated environmental impacts [3], social implications [4,5], and security of their supply [6]. The extraction and processing of raw materials itself results in over half of global greenhouse-gas (GHG) emissions and more than 90% of global water stress and biodiversity loss [3,7]. Current scenario work by the United Nations and the Organization for Economic Co-operation and Development (OECD) estimates that raw material extraction could further double to approximately 160 to 180 Gt by around mid-century [7–9].

Raw materials are important to reach many environmental and socio-economic goals as proposed by the United Nations 2030 Agenda for Sustainable Development [10,11]. They are also required for the transformation towards achieving the climate targets under the Paris Agreement [12–14]. However, the provisioning of materials can also entail impacts which might hinder achieving such goals [11].

The material criticality studies developed in recent years have explored economic, geo-political, and technological factors that could affect the raw materials' security of supply [6,15]. It is argued that governance is a proxy for also social and environmental considerations in related screening-level assessments [16]. Other work has focused on developing more explicit environmental risk-related indicators that could be used in criticality assessments [17]. Environmental and social pressures can also play a role in the materials' security of supply and present obstacles to a future transition to a low-carbon society. Indeed, sudden supply chain disruptions, such as, e.g., during the current Coronavirus pandemic or due to natural disasters or geo-political tensions, can suddenly alter material availability. Conflicts can also prevent access to mineral deposits; accidents and environmental damage compromise public acceptance and can hinder future extraction operations.

As highlighted by Ali and colleagues [18], social and environmental factors, as well as a lack of legislative, economic, and governance stability in the host countries, might increasingly threaten the capacity of the extractive industry to cope with a growing global demand for raw materials. Hence, social conflicts, human rights issues (like, for instance, child labor), governance problems, and environmental impacts are among the factors that should be monitored for preventing price peaks or supply disruptions in the future. From the industry perspective, companies increasingly evaluate and report environmental and social performance [19]. Responsible sourcing of minerals and supply chain due diligence are sometimes integrated in companies' risk management strategies [20].

Adverse environmental impacts and risks of primary materials provisioning can be reduced through a number of approaches. One of them is the use of recycled materials for meeting demands due to the potentially lower environmental impacts of secondary materials provisioning when compared to primary raw material production. However, current recycling rates for many materials are rather low globally [21] and also in regions where waste management practices are well developed, like, e.g., in Europe [22]. Increasing product complexities, in terms of the number of materials often used only in small amounts in single products [2], proves challenging from a technical and economic standpoint for materials recovery from end-of-life products [22]. Furthermore, a continued growth of anthropogenic material stocks coupled with increasing overall demands limits the potential of secondary materials to displace large fractions of primary material input in the near to medium-term future [22,23]. Other approaches towards a more sustainable materials system include, e.g., lifetime extensions, dematerialization and efficiency strategies, substitution, and component reuse and repair [24]. Furthermore, policy measures to promote life-style changes (sufficiency) also represent an important component of a sustainable materials system, but life-style changes are less frequently discussed in the literature and by policy making (see, e.g., the GreenLife scenario in [13] and other literature [25,26]).

In addition to the above mentioned trends (growth in absolute material demands, associated environmental and social implications, and increasing product complexities (i.e., the number of materials used in single products)), also supply chains themselves are becoming increasingly complex as many countries and economic sectors are involved in the provisioning of final products. This makes it more challenging to track and manage material flows and associated impacts. An example is shown in Figure 1 for the material flows of aluminum including the associated trade networks.

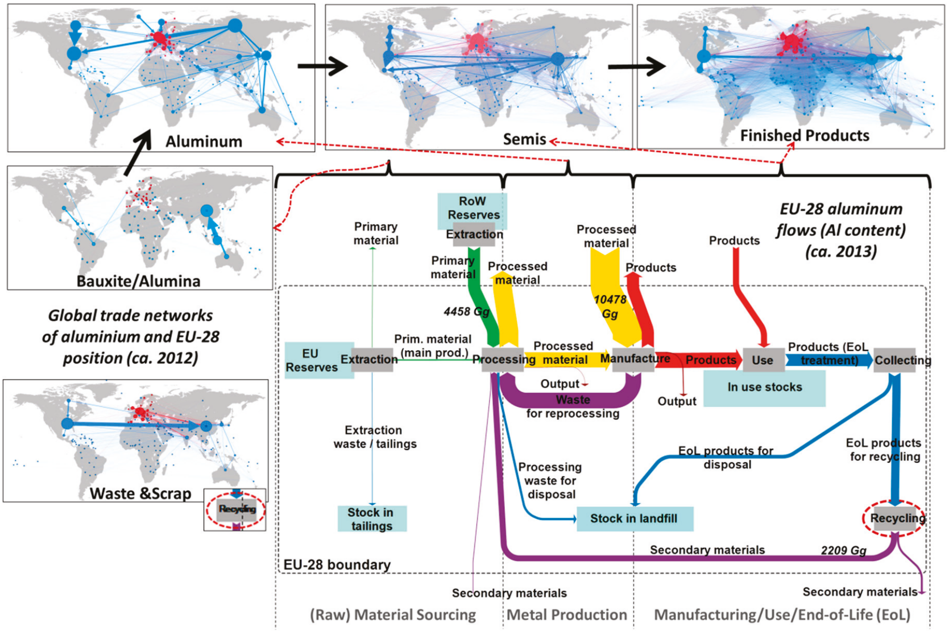

Figure 1. Schematic figure showing selected material flows (Sankey diagram) and the associated physical trade network of aluminum by life-cycle stage (physical trade flows are colored by source country, arrows are proportional to flow size, and node size is based on the sum of imports and exports) (Source: combination of the EU Material System Analysis [27] and trade network visualizations from the EU Raw Materials Scoreboard [28] based on data provided in [29,30]. Details of the Sankey visualization of aluminum are provided in [27], visualized using eSankey (www.ifu.com/en/e-sankey/). Physical trade networks by life-cycle stage were created using data from UN Comtrade [29] together with metal contents provided by Liu and Mueller [30] (see the methodological notes in the EU Raw Materials Scoreboard [28]) and visualized using Gephi [31].) Gg: Gigagrams.

Aluminum finds widespread use in applications such as vehicles, industrial equipment, construction, and metal products. Recycling (shown with purple arrows in Figure 1) is fairly high [27]. Physical trade intensifies, moving from the mining stage to metals production and subsequent manufacturing stages as quantified by the trade network densities [28]. This shows the materials' pervasive use in modern economies. The EU role in the global physical trade networks of aluminum is most prominent at later supply chain stages (i.e., during the manufacturing of semi-finished and final products), and in the trade of aluminum waste and scrap. Supply chain monitoring is required to track the origin of materials and manage material stocks and flows more wisely [32]. At the EU-level, the material system analysis (MSA) tracks the material flows and stocks for a wide range of materials [27,33] and has been incorporated, e.g., into the EU Raw Materials Information System (https://rmis.jrc.ec.europa.eu/?page=msa). The EU MSAs also provide the basis for a number of indicators of the EU criticality assessment [16] and EU circular economy monitoring framework [34].

1.2. Aim of This Special Issue

Against this background, the aim of this Special Issue is to provide a collection of recent research contributions on the topic of (future) raw materials needs and responsible sourcing. This includes the consideration of environmental and social aspects in the management of raw material supply chains and an outlook to anticipated raw material demands in the coming decades. A particular emphasis is given to the requirements for materials in environmental and low-carbon technologies.

In this editorial paper we, firstly, provide a brief overview of the anticipated role of raw materials for achieving the United Nations Sustainable Development Goals (SDGs) [35] and implementing the Paris climate targets for reducing greenhouse-gas (GHG) emissions and the associated rise in global average temperature to well below 2 °C [14]. Secondly, we briefly summarize some of the relevant actors and policies both at the global and EU-level that aim at grappling with the challenges of future raw material supply and demand. Finally, an overview of the papers in this Special Issue is then provided.

2. The Role of Raw Materials for Future Societies

2.1. Raw Materials and the Sustainable Development Goals (SDGs)

Modern societies rely on a wide range of materials that compose the physical basis of economic systems. The variety of materials used has been limited to a few materials for most of the history of civilization. Yet, over the past century, the amount and variety of materials used has been increasing and has experienced a drastic surge in the last decades [28].

In a recent study [11], we mapped the role of raw materials to each of the SDGs proposed in the UN 2030 Agenda [10]. The SDGs represent the vision for future sustainable societies and a guide for policy making at all levels. The analysis takes into account the whole life-cycle of materials, including their production (i.e., the role of economic sectors producing raw materials towards each goal), their consumption (i.e., their function in the use phase), and their end-of-life. The review gathers evidence of impacts occurring in the phase of material extraction and manufacturing, and those affecting the environment and societies.

Regarding the manufacturing phase, pollution and safety at work can be pointed out as the main concerns. Biodiversity impacts, conflicts with indigenous populations, and exacerbation of competition for land and water are instead more typically occurring in the extractive industry (here referring to forestry and mining and quarrying). The role of responsible business conduct and corporate responsibility appears to be crucial in order to determine or prevent these impacts. For instance, sustainable forest management can drive positive contributions to various goals including, for instance, creation of jobs, maintenance of ecosystem services, climate change mitigation, etc. Similarly, governance and institutions have a very relevant role in translating natural resource endowment into national wealth [36,37]. The mining industry can contribute to economic development through the payment of royalties, employment creation, and the provision of infrastructure and services to local populations, especially in developing countries, if good governance of natural resources is in place.

The study also highlighted the contribution of materials in achieving several goals related to society well-being and prosperity. This includes their direct contribution to some goals like the creation of employment and economic growth (Goal 8: Decent work and economic growth) and the provision of materials for infrastructure (Goal 9: Industry, innovation and infrastructure). In addition, the function of materials in specific applications indirectly contributes to other economic, social, and environmental goals. This is the case of non-replaceable materials used in medical devices (that contributes to Goal 3 on Good health and well-being), in low-carbon energy technologies (contributing to Goal 7 on Affordable and clean energy and Goal 13 on Climate action), or in environmental technologies like water treatments (contributing to Goal 6 on Clean water and sanitation), just to cite some examples.

The societal role of materials is partially captured by the concept of Critical Raw Materials [6]. The current assessment methodologies for criticality, however, are often based on factors related to supply risks and, e.g., the materials' economic importance. Other factors beyond economic importance are not explicitly assessed in relation to the functions of materials in/for societies. As argued by the contribution of Schellens et al. [38] in this Special Issue, a holistic definition of "critical materials" could allow for the consideration of, e.g., the socio-cultural and ecosystem support functions of natural resources that could bring a different prioritization of materials.

Finally, proper materials management is pivotal for Goal 12 on "Responsible consumption and production". This goal includes the targets on sustainable management and efficient use of natural resources (Target 12.2, measured through the material footprint and the domestic material consumption) and on reduction of waste generation through prevention, reduction, recycling, and reuse (Target 12.5, measured through national recycling rates and the amount of materials recycled). Resource efficiency [39], a circular economy [40], and decoupling of material use from economic growth [41] are pointed out as instrumental strategies to avoid overextraction and degradation of environmental resources.

2.2. The Role of Raw Materials in a Low-Carbon and Resource Efficient Society

Low-carbon energy and transport technologies rely heavily on the use of critical materials. By 2050, e.g., more than 1 billion electric vehicles, and the increased use of electricity for heat and renewable hydrogen are expected as the main drivers for increased electricity demands from renewables [42]. For this, annual solar photovoltaics additions might need to increase from currently about 109 GW/yr to 360 GW/yr in 2050 and annual wind additions from about 54 GW/yr today to 240 GW/yr in 2050 [42]. As, e.g., renewable energy systems are substantially more metal-intensive than existing power generation [12], a transition to a low-carbon society requires an upscaling of current mining of several metals and metalloids [43,44].

Authors have emphasized that this could hinder the transition to a low-carbon economy [45]. For example, using dynamic material flow analysis, Elshkaki and Graedel [46] found that for renewable electricity generation technologies the global supply of base metals (aluminum, copper, chromium, nickel, lead, and iron) could be met in the GEO3 Market First and Policy First scenarios, while constraints in the supply of silver, tellurium, indium, and germanium could limit the introduction of certain photovoltaic (PV) technologies. For seven major metals (i.e., iron, manganese, aluminum, copper, nickel, zinc, and lead), demands are expected to double or triple relative to 2010 levels by midcentury [47]. Using wind, solar, and energy storage batteries as proxies, the World Bank has examined metal demands into the future [48].

Similarly, one recent assessment concluded that projected demand for 14 metals, such as cobalt, lithium, rare earths, nickel, and copper, which are crucial for renewable energy, storage, and electric vehicles could rise dramatically in the next few decades [49]. Another study analyzed demand for 12 metals in solar power, wind power, and electric motors, and batteries in global climate change mitigation scenarios up to 2060 [50]. With regard to low-carbon energy and transport technologies at the EU-level, moderate supply issues are expected for indium, silver, and silicon in PV technologies, and for cobalt and lithium in electric vehicles until 2030 [51]. In addition, bottlenecks for carbon fiber composites were found [51].

A recent study by de Koning and colleagues highlights that annual metal demand for electricity and road transportation systems may increase significantly for indium, neodymium, dysprosium, and lithium [43]. In Germany, the demand for metals due to new technologies (e.g., batteries, renewable energy, superalloys, diodes, medicine, etc.) is expected to lead to significant demand surges for germanium, cobalt, scandium, tantalum, neodymium, praseodymium, and a range of other metals until 2035 [52]. For lithium, dysprosium, terbium, and rhenium, the demand of the German economy might be more than twice the primary production in 2013 [52].

However, most studies to date focus on the transformation of the energy system or a subset of "emerging technologies" and do not consider potential material demands across all economic sectors and the necessary build-up of infrastructure required to reach GHG neutrality until 2050. Exceptions include a recent report by the German Environment Agency which provides a systematic assessment of material requirements for a GHG-neutral and material-efficient Germany in 2050 using scenarios analysis [13]. A recent report of the European Commission forecasts raw material needs for various technologies (e.g., batteries, wind turbines, PV) and sectors (e-mobility, renewable energies, defense, and space) in 2030 and 2050, and briefly discusses competitions between those [53].

Recent research also shows that sustainable materials management (i.e., implementing measures related to material efficiency, reuse and recycling, product lifetime extensions, light-weight designs, substitution, and others) has the potential to positively contribute towards the mitigation of GHG emissions and needs to be considered in climate change mitigation approaches [54–58]. This has, until recently, been overlooked in policy discussions on climate change mitigation [59]. Another recent paper demonstrates that re-use of batteries arising from electric vehicles in stationary applications has the capacity to increase resource efficiency of raw materials but can postpone significantly the availability of secondary raw materials [60]. Future policy developments should consider the synergies between sustainable materials management with other policy areas (e.g., climate change, biodiversity, energy, agriculture, etc.) and design them in an increasingly integrated fashion.

3. Global and EU Policies for Sustainable Materials Management

Global level. The United Nations Framework Convention on Climate Change (UNFCCC) Paris Agreement was adopted in 2015 with the goal to keep the increase in global average temperature well below 2 °C [14]. However, policies currently in place seem insufficient for achieving this goal [61]. Recognizing that the successful delivery of the UN SDGs and implementation of the Paris climate targets requires technologies that depend on a wide range of minerals in vast quantities [18], an increasing number of institutions and activities are forming at the global level looking into possibilities for more sustainable resource management.

These activities include, e.g., the United Nations Environment Programme (UNEP) International Resource Panel (IRP), which was formed in 2007 with the mission to consolidate and evaluate scientific data in order to provide global guidance for the sustainable management of natural resources [41]. The Intergovernmental Forum on Mining, Minerals, Metals and Sustainable Development aims at supporting mining for sustainable development to limit negative impacts and ensure that financial benefits are shared [62].

Several high-profile multilateral initiatives emphasize the importance of resource productivity. The G7 (an alliance of seven major industrialized countries) has established an "alliance on resource efficiency" at Schloss Elmau in 2015, which formed the basis for the adoption of the Toyama Framework on Material Cycles in 2016, and the Bologna Roadmap in 2017 [63]. Similarly, the G20 decided to establish a "G20 Resource Efficiency Dialogue" at their summit in Hamburg (Germany) in July 2017 [64]. The dialogue aims at making the efficient and sustainable use of natural resources a core element of the G20 talks. In the fourth Session of the United Nations Environment Assembly (UNEA4), the international community adopted a number of resolutions with relevance to resource efficiency (e.g., resolution UNEP/EA.4/RES.1 on innovation pathways to achieve sustainable consumption and production, or resolutions UNEP/EA.4/RES.7 and UNEP/EA.4/RES.9 on environmentally sound waste management and addressing single use plastic products pollution [65]). The Organization for Economic Co-operation and Development (OECD) promotes the sustainable use of materials and reduction of their negative environmental impacts by encouraging resource productivity and waste management, e.g., through the development of material flow and waste databases, related indicators, and the publication of working papers and reports (http://www.oecd.org/environment/waste/). Moreover, the OECD issued the "Due Diligence Guidance for Responsible Business Conduct" [66], which are non-binding recommendations for enterprises willing to understand and implement due diligence on a wide range of risk areas: human rights; employment and industrial relations; environment; bribery, bribe solicitation, and extortion; consumer interests; and disclosure. Sector-specific guidance has also been released for a number of sectors, including mining. The OECD "Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High-Risk Areas" [67] is often considered the international standard for due diligence in the mineral supply chains and underpins the EU Regulation on Conflict Minerals (Regulation (EU) 2017/821 of the European Parliament and of the Council of

17 May 2017, laying down supply chain due diligence obligations for Union importers of tin, tantalum, and tungsten, their ores, and gold originating from conflict-affected and high-risk areas).

The World Bank has enacted the Climate Smart Mining Facility, which supports the sustainable extraction and processing of minerals and metals by scaling up technical assistance and investments in resource-rich developing countries [68]. The World Resources Forum and Future Earth are bringing together academics, policy makers, and industrial representatives to grapple with the science of sustainable resource use. A responsible and sustainable sourcing of raw materials is also called for by the Council Conclusions on Convention on Biological Diversity (CBD) of October 2018, in order to reconcile the extractive sector with the protection of ecosystems and biodiversity in producing countries (Council conclusion 12948/18).

With the active support of the EU, the United Nation Environmental Assembly adopted in March 2019 in Nairobi a resolution on mineral resource governance [69]. The resolution acknowledges the role of sustainable management of metal and mineral resources for the development of clean technologies and therefore to the climate change action and the decoupling of economic growth from environmental degradation. Moreover, it encourages governments, businesses, non-governmental organizations, academia, etc. to promote “due diligence best practices along the supply chain, addressing broader environmental, human rights, labor, and conflict-related risks in mining, including the continuous increase of transparency and the fight against corruption”.

EU-level. The 2008 EU Raw Materials Initiative aims at ensuring: (i) a fair and sustainable supply of raw materials from global markets; (ii) sustainable supply of raw materials within the EU; (iii) resource efficiency and supply of ’secondary raw materials’ through recycling [70]. This approach recognizes the role of raw materials for the functioning of the industrial system and its competitiveness. At the same time, it stresses that sustainable production and a circular economy are needed in order to achieve security of supply.

The “Europe 2020 strategy” and its related flagship initiatives outline the vision of promoting resource-efficiency in Europe and shifting to a greenhouse-gas (GHG) neutral economy [71]. The EU Circular Economy Strategy (e.g., encompassing an action plan, monitoring framework, and plastics strategy) followed as the basis for overall materials management at the EU level [72]. The energy roadmap outlines possible routes towards decarbonizing the energy system by 2050 [73]. Recently, a long-term vision for a climate-neutral Europe was published [74] and a strategic action plan on batteries was adopted [75]. This “EU strategic long-term vision for a prosperous, modern, competitive and climate neutral economy” (COM(2018) 773 final) stresses the role of raw materials for climate action. While it acknowledges that primary raw materials will continue to provide a large part of the demand, resource efficiency and a more circular economy are expected to improve competitiveness, create business opportunities and jobs, reduce energy requirements, and in turn, reducing pollution and GHG emissions.

Currently, the EU Green Deal (COM(2019) 640 final) provides a roadmap with actions towards a competitive economy in which GHG neutrality is reached by 2050, economic growth is increasingly decoupled from resource use, and no person/no place is left behind [76]. Within the Green Deal, the EU sets actions to promote a sustainable and inclusive growth. Among them is a new circular economy action plan [77], a new industrial strategy for Europe [78], and a proposal for a climate law [79].

Examples of instruments for the promotion of responsible sourcing at the EU level include the Conflict Minerals Regulation (EU 2017/821), which tackles the specific issues of 3TGs (Tungsten, Tantalum, Tin and Gold) and will be effective from 2021; the Strategic Battery Action Plan (COM(2018) 293 final, Annex 2), which promotes ethical sourcing of raw materials for the batteries industry and the related European Battery Alliance (EBA), launched in 2017 to create a competitive battery manufacturing value chain in Europe; and the research program Horizon, including the research project RE-SOURCING (Global Stakeholder Platform for Responsible Sourcing). Moreover, in 2019, the European Commission launched “Due Diligence Ready!”, an online portal that provides businesses with guidance on how to check the sources of the metals and minerals entering their supply chains.

Various additional EU and national policies in member states related to material use and resource efficiency exist, and an overview is provided elsewhere [80–83].

4. Towards Low-Carbon and Material-Efficient Societies

Recent policy developments in the EU, such as covered in the EU Green Deal [76–79] as well as climate and energy policies of individual member states, have set out the ambitious goal of achieving climate neutrality by 2050. This will only be possible through a rapid transformation of all economic sectors towards low carbon technologies, by increasing material efficiency across a wide range of materials, technologies, and sectors, and by changes in life-styles. While research in the design of 100% renewable energy systems has gained increasing attention since 2004 [84–87], an integrated view of the associated materials and other resources demand (water, land area, biodiversity, etc.) [88], associated social and economic implications [19], as well as the potential of material efficiency to contribute to climate mitigation [89], have only recently been considered. Some scenarios and modeling approaches exist to highlight the impact of future development paths towards multiple SDGs, highlighting potential trade-offs that might not be visible when focusing only on a subset of impact categories [90,91].

Determining options for reducing GHG emissions and resource use within an economy requires, firstly, a screening across all economic sectors (i.e., energy, mining, manufacturing, transportation, agriculture, buildings and infrastructure, waste management, etc.) to determine possibilities for implementing material efficient and renewable (low-carbon) systems. Substitution roadmaps are central to complement efficiency and recycling approaches [92]. Given the long lifetimes of large-scale systems, such as power plants or steel production, an implementation of alternative solutions has to take place within the next years if climate goals under the Paris Agreement until 2050 are taken seriously. This includes, e.g., the switch to renewable energy and towards the use of power to gas/liquid (for gas, fuels, and chemical feedstocks provisioning from renewable power) in the energy sector and across industrial applications, e-mobility and better public transport, and life-style changes (e.g., reduced meat consumption, increased on-ground public transport for shorter distances instead of aviation, traffic avoidance, sufficiency, etc.). Research shows that an economy-wide transformation across all sectors is technically feasible (at least for single countries and regions) but that it requires rapid and ambitious implementation on the policy side [13,84].

Providing scenarios and roadmaps that describe the technical, life-style, and policy changes required to achieve GHG neutrality by 2050, while at the same time closely monitoring potential pressures through other natural resource demands, is an important step in laying out technically feasible visions for individual countries and regions. Stakeholder engagement is essential to have broad societal support for such a vision.

Furthermore, sound data and indicators are crucial to understand possible trade-offs between different material and technology choices with regard to environmental and social implications. By capturing the flows and stocks of individual materials [32] or broad material categories [93], material flow analysis (MFA) provides a good starting point for better managing (raw) materials, avoiding losses to the environment, and for assessing social considerations. Efforts by governments are underway at various spatial (globally, regionally, and for individual countries or sectors/industries) and temporal scales to capture material flows in the economy (e.g., [27,32,33,94–97]). Frameworks for the description and monitoring of the physical economy are emerging [98].

In the life cycle assessment (LCA) methodology, physical accounts of materials and energy inputs and outputs in a system can be combined with unitary factors of impact (i.e., characterization factors (characterization factors express how much a single unit of mass of the intervention contributes to an impact category)) in order to help assess impacts over the life-cycle [99]. At the level of products or companies, product and organizational environmental footprints provide both a concept and data for estimating environmental impacts supporting, e.g., corporate reporting and investment [100,101]. Looking at socio-economic aspects, the social life cycle assessment (S-LCA) methodology similarly combines site-specific and generic data on social aspects affecting different types of stakeholders in order to help identify impacts in the supply chain [102]. Both techniques are based on the design of a system from a physical point of view, the definition of its burdens, and the consideration of all the life-cycle stages, which facilitates detection of burden shifting and comparison of alternatives. Moreover, a wide spectrum of impact categories is addressed by both environmental and social LCA. Availability and quality of data remains, however, one of the main constraints, as both LCA and S-LCA require extensive gathering of primary data in order to get to robust results. Indeed, in the case of social assessment, contextual information is essential and generic data from commercial databases can support a first screening of hotspots but are not sufficiently accurate to perform an impact assessment [103].

5. Overview of Papers in This Special Issue

The contributions gathered in this Special Issue address the following aspects: (i) assessment of material requirements for future energy systems; (ii) reflection on the concepts of resource depletion and criticality; (iii) analysis of social and environmental pressures of mining; (iv) analysis of conflict minerals management from a company perspective; and (v) analysis of a circular economy through material flow cycles.

Concerning the first group, these papers quantify material requirements to support efficient transport systems [104] (Teubler et al.), renewable energy technologies [105] (Moreau et al.), or low-carbon electricity generation [106] (Boubault and Maïzi). Different time frames are considered (respectively, 2030, 2050, and 2100). Teubler et al. [104] quantify the annual final energy and GHG-emission reductions from low-carbon transport in Europe in 2030. Moreover, they compare these reductions to the savings and additional requirements for materials and metals using indicators like material footprints, carbon footprints, etc. Boubault and Maïzi [106] use life-cycle inventories of technologies for energy generation and the TIME Integrated Assessment Model to project the global raw material requirements in two scenarios (a second shared socio-economic pathway (SSP2) baseline and a 2 °C target scenario). Moreau et al. analyze the material requirement of a transition to a renewable energy system, taking into account five energy scenarios. The storage capacity needed to support renewables is also modeled. The material requirement is then compared with the availability of metal reserves and resources, reflecting on the implications on resource depletion.

Resource depletion is also at the core of the Rötzer and Schmidt paper [107]. Using historical data on ore grades, prices, mining technologies, etc., they argue that decreasing metal ore grades should not be considered as indicators of resource depletion, as they are often addressed through technological advancement in mining techniques. However, the increasing environmental impacts, and resource requirements related to the exploitation of lower concentrated deposits (which can imply competition for water and land, and lead to social tensions and/or impacts) should be looked at as the main concern.

Schellens and Gisladottir [38] discuss another feature of raw materials that has been gaining growing importance in the last decade, especially from a policy perspective, i.e., raw materials criticality. Their investigation focuses on the current definitions, and suggests that the current discourse on criticality overemphasizes some aspects, like the economic importance of materials (instead of their social and ecological function), the role abiotic materials (instead of biotic), etc. A holistic definition of natural resource criticality is proposed to provide decision-makers with neutral and balanced information and recommendations on natural resource management.

Social and environmental pressures linked to mining are investigated in the paper by Di Noi and Ciroth [108]. This paper presents a sustainability hotspot screening for the EU Horizon 2020 "Integrated Mineral Technologies for More Sustainable Raw Material Supply" (ITERAMS) project, which targets more efficient water recycling, tailings valorization, and the minimization of environmental footprints.

Looking at the downstream part of the metals supply chain, Young et al. [109] gather data from smelters and manufacturing industries to explore how these industries manage conflict minerals and perform due diligence programs. This investigation sheds light on the implementation of responsible sourcing from a company perspective, providing insights on supply chain transparency and risk management for what concerns human rights violations, conflicts, poor governance, etc.

Finally, in Graedel et al. [110], the Australian anthropogenic cycles of five materials (four metals and one alloy) were analyzed and utilized to provide novel insights into the circular economy potential for each of the cycles and carbon neutral prospects in Australia. The study demonstrates that the circular economy must be conceived at the global level, and must be cognizant of the losses that are inevitable at every life stage.

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resources

Article

Metals for Fuels? The Raw Material Shift by Energy-Efficient Transport Systems in Europe

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Abstract: The long-term transition towards a low-carbon transport sector is a key strategy in Europe. This includes the replacement of fossil fuels, modal shifts towards public transport as well as higher energy efficiency in the transport sector overall. While these energy savings are likely to reduce the direct greenhouse gas emissions of transport, they also require the production of new and different vehicles. This study analyses in detail whether final energy savings in the transport sector also induce savings for material resources from nature if the production of future vehicles is considered. The results for 28 member states in 2030 indicate that energy efficiency in the transport sector leads to lower carbon emissions as well as resource use savings. However, energy-efficient transport sectors can have a significant impact on the demand for metals in Europe. An additional annual demand for 28.4 Mt of metal ores was calculated from the personal transport sector in 2030 alone. The additional metal ores from semiprecious metals (e.g., copper) amount to 12.0 Mt, from precious metals (e.g., gold) to 9.1 Mt and from other metals (e.g., lithium) to 11.7 Mt, with small savings for ferrous metal ores (−4.6 Mt).

Keywords: energy-efficient transport; greenhouse gas (GHG) emissions; material resources

1. Introduction

The transport sector in Europe is responsible for one quarter of the region's greenhouse gas (GHG) emissions. A transition towards low-carbon transport alone would enable a 60% reduction until 2050 compared to 1990 [1]. Existing policies work towards this goal. They promote, for example, low- and zero-emission vehicles or a switch to alternative energy for transport.

From a technical point of view, this translates into fewer and other vehicles (modal shift). These vehicles are either more fuel efficient or powered by alternative sources of mechanical energy. While these steps help to reduce the direct GHG emissions in Europe, there are some indications for additional indirect emissions (e.g., from electricity supply and battery production) as well as unintended side or rebound effects from this transition strategy. The study at hand intends to shed light on some of these effects and to assess their criticality in regard to future material use in Europe and abroad.

One major concern of researchers is the additional indirect GHG emissions from non-operational infrastructures, fuel provision and vehicle manufacture. Chester and Horvath (2009), for example, found that GHG emissions and energy use are influenced by non-operational aspects. The overall GHG emissions are 1.4–1.6 times higher for road transport and 1.8 to 2.5 times higher for rail transport in the US [2]. Renewable electricity and lower material intensities of transport infrastructure and manufacturing could reduce GHG emissions and emissions from air pollutants such as SO_2 and NO_X. Other authors (Williams et al., 2012) emphasize that low carbon transitions require a logical deployment sequence in order to be successful. Energy efficiency is followed by decarbonization of energy supply and the electrification of fossil energy use [3].

These findings go hand in hand with research on effects from the production of electrified vehicles and their infrastructure. A recent study on behalf of the European Environment Agency [4] analyzed the interactions of electric vehicles and the power sector in Europe. The authors quantified the net emissions from an increased number of electric vehicles. They conclude that with an increased share of electric vehicles, the electricity demand of these cars becomes a relevant factor in the energy system. The positive GHG effects are partially offset by the additional demand.

The affected systems and impacts of low-carbon mobility are widely discussed in the literature. Bohnes et al. (2017), for example, found that environmental burden shifting can take place if electric vehicles are deployed to a large degree. The electrification of passenger transport can also have unintended side effects in cold countries. Additional energy for car heating might be required, as vehicles with an internal combustion engine are more energy-efficient in this regard [5]. It is also possible that direct and indirect price effects lead to a rebound effect from a microeconomic point of view. Vivanco et al. (2014) analyzed the price elasticity of transport demand and marginal consumption models. They showed that some technologies for electric vehicles can lead to partial or over-compensation for some environmental impacts [6].

In regard to natural resources, raw materials and the economic effects of low-carbon transport, several studies focus on metals (e.g., lithium). Tagliaferri et al. (2016) analyzed the environmental impacts of conventional and electric vehicles in a cradle-to-grave life-cycle assessment (LCA) [7]. They found that higher toxicology impacts for electric vehicles are linked to the use of precious metals and chemicals in the battery-manufacturing phase (GHG emissions and abiotic depletion are reduced with the help of battery electric vehicles, but are more influential during the production phase). Olivetti et al. (2017) put their research focus on the future material requirement for lithium-ion batteries. They conclude that manganese and nickel supply is sufficient to meet these requirements [8]. For lithium itself, it is not the quantity of reserves that poses a challenge, but the slow increase in production compared to the high increase in demand. The authors are confident that this is only a bottleneck in the short term. Another potential bottleneck is the material requirement for cobalt. The mining and refining of cobalt is currently highly concentrated in certain regions (Democratic Republic of the Congo (DRC) and China).

The metal availability for future low-carbon transport also depends on similar transitions in other sectors. In this context, several studies analyzed the future demand of metals such as lithium or neodymium [9–13]. It is assumed that these issues can be overcome with an upscaling in metal production. However, there is a need for further analysis of the trade-off between reducing GHG emissions on the one hand and the additional material demand from technologies towards electrification.

The authors of this study follow up on this question by analyzing the results of a multiple-impact analysis of future energy efficiency improvement actions in Europe in 2030 (Calculating and Operationalizing the Multiple Benefits of Energy Efficiency in Europe (COMBI)). With respect to the transport sector, it is investigated whether future transport systems require additional metal ores to be produced and which metals might be needed in particular. Are we required to trade metals for fuels?

The consequences of such a trade could affect different aspects of more sustainable economies. Further increasing the extraction rates of metals would increase the associated environmental burden itself and the burden shift towards developing countries (which often provide the metal ores). Bottlenecks in particular could amplify these effects, as metal costs increase and less favorable reserves (lower ore grades) are tapped in order to meet the demand. This could, in turn, lessen the positive effect of many sustainable policies on a global scale. However, it could also be an additional incentive for countries to promote higher material efficiency and material recovery rates in their economies (including the development of cost-effective recycling technologies).

The study is subdivided into 6 sections. The introduction in Section 1 is followed by a description of the scope of the study in Section 2. Section 3 covers impact-indicators, methods, data, models and limitations. Section 4 describes the results and Section 5 discusses the implications for metal demand and supply. Section 6 concludes the study with an aggregation of the findings and the need for future research.

2. Scope

The core results in this paper are part of the Horizon 2020-project COMBI. COMBI aims at calculating the energy and non-energy impacts 21 energy efficiency improvement (EEIs) in the 28 European Union members (EU-28) in 2030. The analyzed impacts cover the areas of air pollution, social welfare, macro economy, energy systems/security and resources (further information such as reports and a tool to visualize the effects, can be found at https://combi-project.eu or [14–16]). They are calculated from a snapshot view. The final energy use in 2030 after implementing EEIs is compared to its equivalent without these measures. The base-case scenario includes activities that are already in motion (extrapolated towards 2030).

For resources, the authors created several bottom-up models to quantify the annual net impacts in terms of raw material extraction and greenhouse gas emissions. These models cover the so-called use-phase of all 21 actions in five sectors. The use-phase represents the difference in resource impacts from two different scenarios: base-case and energy-efficiency. They are based on final energy savings, but also the necessary material and energy flows to provide the energy services. This includes, for example, the construction of power plants and grids for electricity in the member states (see pp. 37–54 in [17]). The calculation method uses the input data (final energy per energy carrier and EEI) and relates this energy consumption to the material and energy flows necessary to provide the energy service. The differences in the flows of both scenarios are then used to calculate the resource impacts (see also section on methods).

In addition to the net effects during the use-phase, several actions were also considered in the context of their production-phase. The production-phase represents the material and energy flows that stem from differences in the product stocks and product types. For passenger and freight transport, production-phase models consider the production of cars, busses, duty trucks and trains (see pp. 55–63 in [17]).

This study focuses on EEIs in the transport sector, which were modeled by the University of Antwerp (see [18,19] for further details). For passenger transport, a modal shift (action 9), future car (action 11) and bus stocks (action 12) were considered. The freight transport activities cover a modal shift (action 13), light duty trucks (action 14) and heavy-duty trucks (action 15). Table 1 shows the list of actions considered, as well as the resulting differences in the final energy use between base-case and EEI scenarios in 2030.

Table 1. List of energy efficiency improvements (EEIs) in the transport sector considered for the study at hand.

Actions ^{a} (EEIs)	Final Energy Saving in EU-28 in 2030 (Baseline vs. EEI)
9—Transport (passenger) modal shift	40 TWh
11—Transport (passenger) cars	284 TWh
12—Transport (passenger) public road/bus transport	3 TWh
13—Transport (freight) modal shift	90 TWh

Table 1. *Cont.*

Actions [a] (EEIs)	Final Energy Saving in EU-28 in 2030 (Baseline vs. EEI)
14—Transport (freight) light duty truck	13 TWh
15—Transport (freight) heavy duty trucks [b]	32 TWh
Total [c] (Actions 9,11,12,13,14,15)	460 TWh (rounded value)

Source: Calculating and Operationalizing the Multiple Benefits of Energy Efficiency in Europe (COMBI) input data [18,19] based on the models: PRIMES [20]; JRC TIMES [21]; TREMOVE [22]; iTREN [23]; ASTRA-EC [24]; SULTAN [25]. [a] The numbering of actions might deviate from other COMBI sources, because it has been changed over the course of the project; all numberings in this paper refer to this table. [b] There are no differences in the product stocks for action 15 in the COMBI input data (the same types of heavy duty trucks are produced in both scenarios). However, changes in the overall amount of heavy duty trucks are also reflected in the data on modal shift. [c] The "missing" action 10 considers energy savings from passenger transport with two-wheelers. As the production of two-wheelers could not be incorporated into a production phase model, it is omitted from the selection of actions for impact quantification (use phase and production phase).

The actions themselves can be differentiated into measures towards structural changes in the mode of transport (modal shift in actions 9 and 13) and changes in the transport systems (road transport in actions 11,12,14,15) [18,19]. Modal shifts in the personal transport sector include a shift towards public transport and to non-motorized transport (cycling, walking). For freight transport, a shift towards rail and waterborne transport is assumed. The actions for road transport address changes in drive train technologies (fewer conventional vehicles with an internal combustion engine). They also cover higher fuel efficiency (eco-driving, increased occupancy levels/load factors, higher fuel efficiency for vehicles) and the use of "green" fuels (more environmentally friendly). Avoiding or reducing the number of trips or trip lengths is not considered.

The two modal-shift EEIs represent growth rates for the different modes of transport (all vehicles including walking and cycling). They are based on PRIMES data. While activity levels (e.g., passenger-km) change between 2015 (base year) and 2030 (both scenarios), they are not different between both scenarios. The same holds true for occupancy levels and loading factors. All of these parameters would affect energy consumption and thus distort the direct impacts of EEIs.

The vehicle-specific EEIs rely on fuel-efficiency improvements and changes in drive-train technologies. Fuel efficiency and fuel share values are based on EU scenarios and models (TIMES by the Joint Research Centre), TREMOVE, iTREN, ASTRA-EC and SULTAN). Changes in the vehicle stocks are based on country-specific shares for all different technologies. They are modeled according to annual new sales for each drive-train technology and transportation mode. Basis for the stock-model are JRC TIMES, TREMOVE, iTREN, ASTRA-EC and SULTAN as well.

The quantified net impacts (see methodology) originate in the EU (see Figure 1). Measures within European countries are the source for a reduction of the country-specific energy consumption. The impacts of providing the energy services and producing necessary technologies are not restricted to the European borders (with exception of direct GHG emissions). Because many energy services require materials from outside of the EU, final energy savings also affect material extraction and emissions on a global scale.

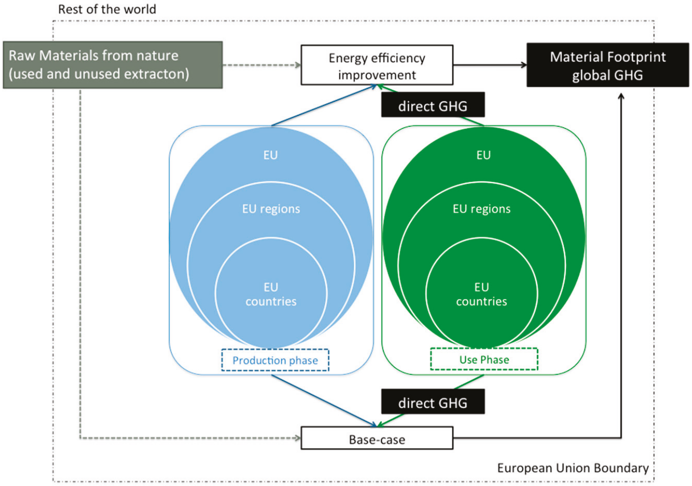

Figure 1. System boundaries for resource impacts material footprint, global greenhouse gases (GHG) and direct GHG (own compilation).

3. Methodology

The quantification required the definition of resource impacts, the selection of methods and the generation of models. A thorough description can be found on the COMBI website (see scope). It contains a literature review [26] as well as a report on methodology (see pp. 14–36 in [17]) and results (see pp. 64–91 in [17]).

3.1. Impact Indicators for Natural Resources

There are several definitions of natural resources and their sustainable use. Most definitions revolve around the usefulness of resources to humans. It is also commonly agreed upon that their depletion affects the environment as well as the needs of future generations. According to the Flagship Initiative under the Europe 2020 Strategy, natural "resources underpin the functioning of the European and global economy and our quality of life. These resources include raw materials such as fuels, minerals and metals but also food, soil, water, air, biomass and ecosystems" [27].

The study at hand restricts natural resource use to raw materials (in tons) and GHG emissions (in tons of CO_2 equivalents or CO2e). The wide variety of environmental and economic effects of resource use cannot be merged into a single indicator [28]. However, the extraction of raw materials on the input side of the techno sphere allow for a rough estimation of resource use effects. Less use of material resources is likely to be accompanied by less pressure on soil, water and ecosystems. A lower global warming potential also indicates a lower environmental footprint in most cases. Functioning as a proxy for a much more complex issue, both impact categories are strongly linked to the EEIs. A more detailed description of advantages and limitations of material flow accounting (MFA) and similar methods (e.g., primary energy demand) can be found in the literature [29–32].

Other potential impact-indicators have been omitted for various reasons. First, any resource indicator for COMBI needed to be applicable to single EEIs within countries and the sum of all EEIs in a country. Second, any resource indicator should have no direct relation to other impacts in the study on multiple benefits of energy efficiency in order to avoid double counting. Third, resource indicators should be able to cover mining aspects as well as biotic raw materials.

Methods based on multi-criteria analysis were ruled out, because they are either non-quantitative assessments or rely on weighting by experts. Energy-related resource indicators were not used for risk of double counting. Methods based on input-output tables on the other hand (e.g., economy-wide material flow accounting) were ruled out due to their high level of aggregation. Many suitable LCA impact categories for resource depletion (such as abiotic depletion potential) are restricted to a selected group of materials and do not cover the mining process or raw materials without economic use. However, future assessments of multiple impacts might benefit from the current work of the task force on natural resources. This expert group is expected to classify and evaluate several resource indicators and relate them to their area of protection (see [33] for present findings).

Table 2 lists the impact indicators. The indicator dGHG refers to the GHG emissions from both scenarios, caused by the combustion of fossil fuels in the transport sector. It is restricted to the use phase of EEIs and the direct consumption of energy carriers. The carbon footprint also includes the life-cycle wide, but annual GHG emissions from energy services and the production of vehicles (use and production phase). It refers to globally induced GHG emissions.

Table 2. Impact indicators for EEIs in the European transport sector.

Impact Indicators [Unit]	Description
Material Footprint [tons]	Biotic and abiotic raw materials from used extraction in use- and production-phases unused extraction of biotic and abiotic materials without economic use in use- and production-phases
Biotic Raw Materials [tons]	Biotic raw material demand from used extraction in use- and production-phases
Abiotic Raw Materials [tons]	Fossil fuel demand from used extraction in use- and production-phases Metal ore demand from used extraction in use- and production-phases Mineral demand from used extraction in use- and production-phases
Carbon Footprint [tons]	Global Warming Potential (GWP 100a) within and outside of Europe in use- and production-phases
dGHG [tons]	Global Warming Potential (GWP 100a) from fossil fuel combustion in Europe in use-phase

Source: [17].

The material footprint (in kg or tons) includes the life-cycle wide amount of extracted raw materials. These materials are either put to an economic use (used extraction) or not (unused extraction from e.g., excavation). It can be further divided into abiotic raw material demands for fossil fuels, minerals and metal ores. This includes for example ore waste after processing as well as the biotic raw material demand. The material footprint is a sum-indicator of material accounting. It adds up the life-cycle wide inputs of specific materials and connects them to their natural occurrence (e.g., in form of a ore) as well as any additional material needed for their provision:

$$\begin{gathered}\textbf{Material Footprint}\text{ (MF)} = \text{Fossil Fuel Demand} + \text{Metal Ore Demand}\\ + \text{Mineral Demand} + \text{Biotic Raw Material Demand} + \text{Unused Extraction}\end{gathered} \tag{1}$$

The final results or net effects are quantified as the difference between both scenarios (see 3.4 models) with help of characterization factors (e.g., the fossil fuel demand of electricity from soft coal in a certain country). This means that sub-impacts can partially compensate each other, such as trading fossil fuels for metal ores.

3.2. Methods

Impact indicators refer to different base-lines throughout EU member states or European markets. Energy-efficiency improvements take place in the same spatial and temporal boundaries. The methods for calculation are based on the material flow accounting and life-cycle assessment methodology.

A additional advantage of these two methods lies in their compatibility. All impacts can be calculated by using characterization factors in the same models from the same input and generic data.

For material footprint the material-input-per-service (MIPS) is chosen (see also [29,34–36]). The necessary impact factors (raw material extraction and unused extraction from nature) are mostly based on Wiesen et al. (2014) [37]. Additional factors are found in an expertise on behalf of the German Environment Agency [38].

The carbon footprint represents the Global Warming Potential for 100 years (GWP 100a) by the International Panel on Climate Change [39]. Direct GHG emissions are calculated by multiplying the direct fossil fuel use in both scenarios with their characterization for GWP 100a. Emission factors stem from a guideline for GHG monitoring by the European Commission [40]. Renewable energy carriers have no direct emissions (dGHG), but can have global GHG emissions for provision and utilization.

Apart from these direct emissions, all impact indicators cover the life cycle phase from extraction to production or cradle-to-gate over the lifetime. They represent a current set of technologies for energy supply and, in case of EE's during the production-phase, for average vehicles and lighting systems in Europe. The functional unit is 1 MWh of net energy or 1000 products.

The phase of decomposition or end-of-life (EoL) is excluded from the analysis. Including the EoL stage would have required data or assumptions for at least the state-of-art, costs and capacities of utilization technologies. It would also require reliable information on secondary material prices and regulatory requirements.

The use-phase, on the other hand, is directly represented by the final energy use in the input data.

3.3. Data

The following data is included in the COMBI input data (not all of which were used to model EEI's in the transport sector):

Final energy use per energy carrier, EEI and country

- Gross energy production in 2030 per country (aggregated data based on PRIMES);
- Stocks of cars, busses, duty trucks, lighting systems per EEI (if relevant) and country;
- Share of ambient heat sources per country;
- V-% of blend for biofuels in 2030;
- loading factors for freight transport vehicles;
- number of lighting points per building in residential and non-residential buildings;
- lighting efficiency of lighting types.

The upstream material and energy flows, including parameters for energy conversion, stem from the Life Cycle Inventory (LCI) database ecoinvent in version 3.1 (The first models were generated as early as 2015. At this point, only ecoinvent 3.1. data was available for the calculation of impact factors for resource use.). Additional data was drawn from EUROSTAT and literature (see section on models).

3.4. Models

The researcher chose a static bottom-up model approach in light of the project's restrictions. Those restrictions required the compilation of input data during impact quantification. The input data itself focused on the effects of energy-efficiency improvements alone. Many surrounding systems were assumed to be the same between scenarios. Dynamic modelling (e.g., feedback loops between sectors) was therefore not possible. The models also exclude the export and imports of energy or products. Each model consists of a set of characterization factors for a country, a region, Europe or one type of product. These factors are then multiplied with the final energy use per energy carrier in the input data or the amount of product type stocks in both scenarios.

The basis for the electricity model is a top-down disaggregation of the gross electricity production in Europe in 2030 (generated within the PRIMES model). The electricity supply by power plants and grids is then further disaggregated bottom-up. Each country is represented by one characterization factor for each impact indicator. However, power plants are, in many cases, representatives of a European region rather than a European country. The same holds true for electric grids, which represent a European average. Additional data stems from ecoinvent 3.1. [41], Eurostat [42], the PRIS database on nuclear reactors [43], wind energy statistics [44], solar power statistics [45] as well as a study on hydropower in Europe [46].

The (transport) fuel model is somewhat simpler, as there are not many differences between European countries in terms of fuel production. This led to the compilation of a European model for fuel provision. Each of the 8 different fuel types in the input data is represented by one average characterization factor for each impact indicator. Additional data for model generation was drawn from ecoinvent 3.1, the JRC well-to-tank/well-to-wheel analysis [47] and the SULTAN model on biofuel substitution of the future [48]. Feedstock data stems a study on biofuel sustainability [49] and information on the natural gas supply in Europe [50].

Additional models were required to represent the production of vehicles in the European market. The COMBI input data provides information on the stocks of 14 different car types (with 3 different sizes each) in both scenarios. A recent study provided the LCIs of 8 different car types [51], which had to be matched to that input data and scaled according to three different sizes (see Tables 3 and 4). The LCI data in [51] is based on several LCAs of vehicles [52–55]. In light of these sources, data on the car body and to lesser extent electrical engines might be outdated.

Additional characterization factors were generated for light-duty trucks (based on the car data), busses (based on a MAN Lion's City M in [56]) and heavy-duty trucks (based on the ecoinvent 3.1. process "production of lorry, 28 tons"). Trains were modeled according to ecoinvent data as well ("goods wagon production" and "locomotive production" for the Rest-of-Europe). All data on vehicles for freight transport was scaled to the country-specific COMBI input data on average load factors (see supplementary materials for detailed information).

Table 3. Matching of drivetrains in the COMBI input data with data from a project on "key technologies for electro mobility" (STROM).

Passenger Car Type in COMBI	Used Drive Train Based on STROM
Internal combustion engine (ICE) gasoline baseline	ICE gasoline
ICE gasoline advanced	ICE gasoline
ICE diesel baseline	ICE diesel
ICE diesel advanced	ICE diesel
ICE liquefied petroleum gas (LPG) retrofit	ICE CNG
ICE compressed natural gas (CNG) retrofit	ICE CNG
ICE ethanol	ICE gasoline
ICE hydrogen	ICE gasoline
Hybrid electric vehicle (HEV) gasoline	Hybrid gasoline
HEV diesel	Hybrid gasoline
Plug-in Hybrid (PHEV) gasoline	Plug-In Hybrid gasoline
Plug-in Hybrid (PHEV) diesel	Plug-in Hybrid gasoline
Battery electric vehicle (BEV)	Battery electric
Fuel cell (FC) hydrogen	Fuel cell electric

Source: [17] based on [51].

Table 4. Scaling of vehicle weight for personal transport.

Type	Weight Class	Weight	Lifetime
Passenger Car	Small	1200 kg	12 years
	Medium	1600 kg	12 years
	Large	2000 kg	12 years
Bus	Standard	11,000 kg	13 years

Source: own compilation.

3.5. Limitations

The chosen approach as well as data availability and matching to the input data resulted in numerous simplifications, assumptions and cut-offs for the models (see Table 5).

Table 5. Key assumptions and cut-offs of models in the study.

Model	Key Assumptions	Cut-Off
Electricity Supply-Use Phase	• All countries use the same network specific (per unit of energy) length and technology for their electrical grid • Power plan technologies of single countries may represent countries within one market • One European process was used to process natural gas into heat and electricity • Country-specific processes do not include upstreams for waste provision, therefore an appropriate process for Switzerland was used for all countries	• Imports and exports of electricity in Europe or between Europe and Rest-of-World • No SF_6 for switching gear
Fuel Supply- Use Phase	• EU-28 average for fuel provision • Direct CO_2 emission factors for each fuel are average in Europe (assuming total combustion) • Share of biofuel in biofuel blends is the same throughout Europe	• No bioethanol from wheat, barley, triticale, wine, cassava • No biodiesel from sunflower, tallow • No natural gas from Turkey, Poland, Romania
Passenger Vehicles-Production Phase	• One product represents one vehicle type in EU-28 • Small, medium, large vehicles are scaled by mass • Standard and advanced cars with internal combustion engine share the same production recipes • Vehicle types differ by types of drive train, not auto body (glider)	
Freight Vehicles-Production Phase	• Light-duty trucks based on large car types in passenger transport model • Heavy duty trucks only represented by one type with different loading capacities per country • Trains represented by one type with different loading capacities per country	• Different production mix for heavy duty trucks in efficiency and base-case scenario (only stock differences by modal shift relate to impacts)

The researchers used current production recipes to generate models of a future use of resources. They neglected potential higher rates of secondary materials in the European economies in the future. This results in the following major limitations in regard to the study itself and their use in another context:

- the generated characterization factors are not a robust basis for a comparison of impacts between countries or technologies by themselves;
- the resulting impact indicators (e.g., net material footprint) depend on the size of final energy use in both scenarios as well as product stocks and the assumption on the share of certain energy carriers (e.g., electricity from soft coal in 2030);
- differences in the LCIs within one product type (e.g., for different battery electric vehicles) can be larger than differences between average product types;
- static bottom-up models cannot account for the fact that changes in the product stocks and final energy use are likely to have an impact on the systems (e.g., the electricity system) themselves as well as extraction and recycling rates of material in a economy.

Other (minor) limitations are inherent to LCA and MFA methods in general (e.g., uncertainty from actuality of data and the use of generic process data), but would also affect other models.

4. Results

The energy efficiency improvements in the transport sector scenarios result in final energy savings in the European Union of 460 TWh in 2030. This results in savings for the overall material demand (material footprint) of 67 Mt (56 Mt for passenger transport alone); 52 Mt stem from a lower raw material demand for fossil fuels; and 12 Mt from a lower demand for materials from unused extraction. There is also the possibility for a small negative trade-off for the extraction of biotic materials. Changes in the provision of final energy lead to an additional demand of 0.4 Mt of biotic raw materials in the use phase. On the emission side, greenhouse gas emissions of 159 Mt CO2e could be saved globally. 135 Mt CO2e could be saved directly from a lower combustion of fossil fuels within the EU.

4.1. Use vs. Production in the European Union (EU)

The changes in the production systems for vehicles attributes to additional global Carbon Footprint savings. 8 Mt CO2e are not emitted globally, resulting in a net carbon footprint of 168 Mt CO2e. However, additional 12 Mt of material have to be extracted during this production phase, decreasing the net material footprint down to 54 Mt. While additional savings could be realized for minerals (1.2 Mt of savings), fossil fuels (1.1 Mt of savings) and materials from unused extraction (5 Mt of savings), the extra demand for 19.9 Mt of metal ores is largely responsible for this effect (see Figure 2). There is also evidence that these transitions lead to an additional demand for biotic raw materials: additional demands of 0.4 Mt are required during use with a net effect of 0.33 Mt.

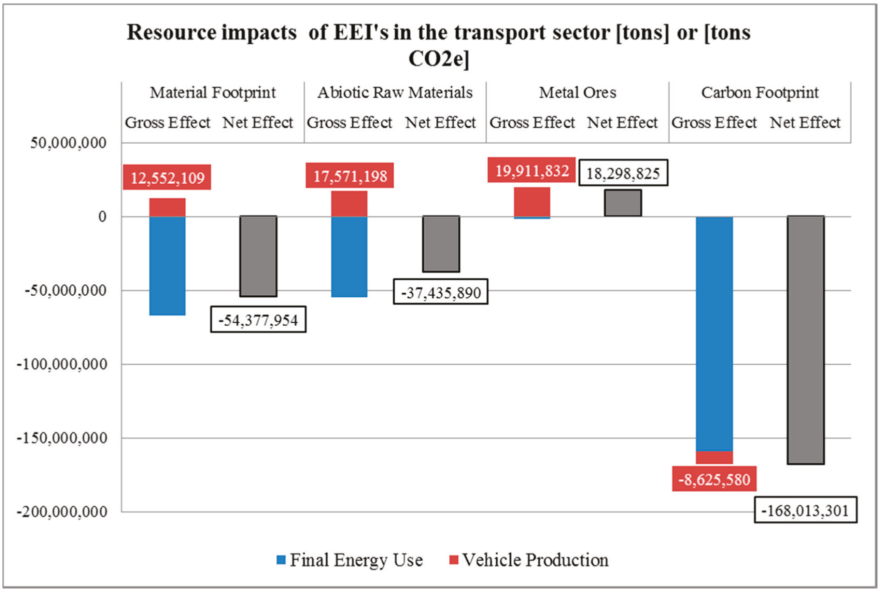

Figure 2. Gross and net impacts of resource impacts in the transport sector (negative values indicate savings). By calculating the differences between both scenarios, single sub-impacts (e.g., metal ores) can be higher than the sum of all sub-impacts combined (see also Section 3.1).

4.2. Material Demand for Modal Shift and Differences in Vehicle Types

The modal shift improvements (action 9 and 13) have a rather small effect on the material requirements of the use-phase. Additional 0.7 Mt are required in the personal transport sector, while 1.2 Mt are saved in the freight transport sector. The overall smaller product stocks from modal shift rather affect the production-phase. The study found additional savings of 53 Mt for personal transport and 61 Mt for freight transport.

Changes from differences in the produced vehicle stocks (actions 11, 12, 14) are mainly responsible for additional material requirements. For personal transport, 56 Mt are saved during use-phase compared to an extra of 106 Mt during the production phase. Light-duty vehicles on the other hand require an additional 18 Mt during the production-phase, but reduce the material demand during the use-phase by 61 Mt.

Looking at the net effect of both sectors (savings of 54 Mt), personal transport only contributes 7% of the savings.

4.3. Metal Ore and Metal Demand

Metal ores are the only material resources that are required additionally in relevant amounts. While EEIs from freight transport induce metal ore savings of 9.8 Mt, an extra of 28.2 Mt of metal ores are needed to provide energy savings in the passenger transport sector in 2030 (resulting in a net effect of an extra 18.3 Mt).

The following sub-sections focus on the metal demand for cars in the passenger transport sector, as this sector alone is responsible for an additional net metal ore demand of 28.4 Mt.

4.3.1. Differences in Car Types and Stocks

Two actions are responsible for metal ore savings and additional metal ore demand from passenger transport in the scenario. Action 9 compares the car stocks in the reference scenario with reduced car stocks from modal shift. Action 11 is compiled from changes in car stocks towards more fuel-efficient vehicles. The total of both actions results in the total net effect. Large differences can only be found for diesel cars (46 million advanced cars in exchange for 57 million baseline cars) and gasoline cars (64 million advanced cars in exchange for 72 million baseline cars). Fewer than 10 million hybrid cars have to be produced additionally. Stocks for full battery vehicles are even negative: 0.2 million cars do not have to be produced as a net effect (although their share in the production mix is significantly higher compared to a reference scenario).

4.3.2. Metal Ore Demand by Metal Type

Despite low differences in car stocks for non-conventional cars, additional metal ores are required to provide energy savings during the use-phase. According to Table 6, additional 28.4 Mt of metal ores are required with savings only for iron ores (4.6 Mt). The additional metal ores from semiprecious metals amount to 12.0 Mt, from precious metals 9.1 Mt and from other metals 11.7 Mt. While the modal shift effect itself saves up to 20.0 Mt of metal ores, an additional 48.6 Mt are required to produce the cars for action 11.

Table 6. Material and metal ore demand (net effects of actions 9, 11 and 9 + 11; negative values indicate savings).

Indicators for Metal Ores	Modal Shift for Cars (A 9)	Production of Cars (A 11)	SUM of A 9 & A 11
Material Footprint	−55.49 Mt	104.81 Mt	49.33 Mt
Unused Extraction	−32.49 Mt	53.07 Mt	20.58 Mt
Metal Ores—TOTAL	−20.17 Mt	48.56 Mt	28.39 Mt
Metal Ores—Iron	−4.96 Mt	0.39 Mt	−4.57 Mt
Metal Ores—semiprecious metals	−5.30 Mt	17.29 Mt	11.99 Mt
Metal Ores—precious metals	−1.90 Mt	11.04 Mt	9.14 Mt
Metal Ores—rare earth metals	−0.01 Mt	0.10 Mt	0.08 Mt
Metal Ores—minor & other metals	−8.00 Mt	19.73 Mt	11.74 Mt

4.3.3. Direct Metal Input

The production of fuel-efficient cars is the cause of the additional metal ore demand in the scenario. The main drivers for the additional requirement of 48.6 Mt in action 11 are hybrid cars (58.1%), fuel cell cars (39.4%) and plug-in hybrids (38.2%), while the reduction in conventional car stocks saves metal ores of up to 17.8 Mt.

The demand for semi-precious metals (12.0 Mt for both actions) is dominated by copper. Copper ores alone contribute 80.3% of this demand. This corresponds to a direct input of 148,000 tons of copper metal and equals 1.0% of the global copper production in 2012 (but 3.6% of Europe's demand in 2014 according to [57]).

For precious metals, an additional metal ore demand of 9.1 Mt would be required. The majority (73.1%) stems from gold ores (coupled production). The corresponding annual direct input for gold only amounts to 11.6 tons of gold, which is 0.5% of the global gold production in 2012 [58], and only 0.4% of the mined gold supply in 2015 [59].

The metal ore demand for minor and other metals (11.7 Mt) is driven by the demand for lithium brines (13.0 Mt). Nickel derivate savings of 2.1 Mt only partially compensate for that. The direct input for lithium amounts to 19,550 tons or 103,000 tons of lithium carbonate or LCE (it is assumed that 1 kg of LCE is equal to 0.1895 kg of pure Li), which is roughly 51% of the worldwide lithium production in 2012. While it seems likely that lithium production will increase of the next decades, demand is likely to increase as well, as more and more lithium-dependent applications evolving (see also [60]).

Cobalt and rare-earth elements are both popular research objects in related literature. Unfortunately, the researchers of this study could not quantify robust results for these metals. The uncertainties from data, methodology and the potential technological development were too high.

4.3.4. Metal Ore Demand for Drive Trains

Many factors in the scenario data were kept on the same level for both scenarios in order to focus on EEIs (e.g., energy mix or activity levels). Additionally, modal shift improvements played a crucial role in reducing the overall demand for cars in the personal transport sector. Only replacing current car technologies with future car technologies would, therefore, have a larger impact on the overall metal demand. Using data in this study on the production of medium-sized cars allows for a rough estimation of these effects. Table 7 shows the comparison between the metal ore demand for a petrol car and the additional demand of other drive trains. However, this risk can be mitigated, if metal recovery and material efficiency are improved.

Table 7. Additional annual metal ore demand per car type compared to a medium-sized petrol car (production of car).

Material Demand	Hybrid, Medium	Fuel Cell, Medium	Battery, Medium
Metal ores (all)	3.1 tons	5.4 tons	6.1 tons
Semi-precious metal ores	1.1 tons	2.0 tons	2.5 tons
Precious metal ores	0.8 tons	0.9 tons	1.0 tons

5. Discussion of Metal Demand and Supply

Table 8 lists the direct metal input results in the study for copper, gold and lithium. It compares them to maximum global production rates in Sverdrup et al. (2017) [58]. Even without considering the uncertainty of the scenario and LCI data, possible technological development as well as higher recycling and more efficient extraction rates, most additional demands for metals are not critical from the perspective of supply.

Trading "metals for fuels" is clearly a possible consequence of low-carbon transport policies, however; in particular, if electrical drive trains (hybrid and battery vehicles) are advocated and lithium remains the most important raw materials for their production. Looking at the literature (e.g., [8,11,61]), it is likely that the future demand for lithium in electrical vehicles exceeds its current production. These additional supply needs can likely be met by an increase in production (also in regard to a comparable large availability). However, lithium is not only required for future vehicles, but also electronic products, thus further tightening the supply in the future.

Table 8. Net direct input for modal shift and car production in the study.

Metal	Net Demand (Direct Input) in This Study in 2030 in [Tons/Year]	Current Production in Sverdrup et al. (2017) in 2012 in [Tons/Year]	Maximum Production Rate in Sverdrup et al. (2017) in [Tons/Year]	Share of Net Demand in the Study Compared to Maximum Production
Copper	148,000	16,000,000	28,000,000	0.7%
Gold	11.6	2600	3200	0.3%
Lithium (LCE)	103,166	200,000	350,000	29.5%

Source: Own compilation based on [58].

Koning et al. (2018), for example, analyzed the demand, production and supply of various metals. They looked at four different scenarios for a low-carbon economy in 2050 (not restricted to the transport sector) [11]. The authors found that the high demand for most analyzed metals (such as aluminum) can be met by the known economic reserves (not without further development of mines, however). In opposition, the demand for lithium and copper (among other metals) cannot be met by current reserves. It was calculated that the global annual demand for electricity production, construction works and land vehicles in 2050 amounts to 18 million tons of copper and 414,000 tons of lithium (supplementary material in [11]); 37 million tons of copper and 1.6 million tons of lithium are required, if also other products such as electronics are considered (data stems from the Blue Map electricity supply (BMES) scenario in the study, which not only considers technological development, but also changes in the electricity supply systems with high shares for renewables and nuclear energy).

Another study by Olivetti et al. (2017) looked closely at the future supply chains of lithium-ion batteries [8]. They emphasized that comparing the demand for lithium to its future supply is not sufficient to determine its criticality. Potential bottlenecks are, rather, likely to stem from an imbalance in production of lithium carbonates in comparison to the demand for battery-grade material. Recycling batteries at the end of life might mitigate the challenges in the lithium supply in the long run, but this is currently economically not feasible.

6. Conclusions

This study quantified the annual final energy and GHG emission reductions from low-carbon transport in Europe in 2030. It compared these reductions to the savings and additional requirements for materials and metals in particular. In regard to the research question (metals for fuels?), additional metal ores are required to allow for energy and GHG savings in Europe and worldwide. The net effect from energy-efficiency improvements in freight and personal transport, amount to an additional demand of ca. 18 million tons for metal ores per year (compared to savings of 54 million tons of fossil fuels). In turn, large global GHG savings of more than 168 million tons of CO_2 equivalent and a lower final energy use of 460 TWh are realized. However, the overall material bill is positive: despite negative net effects for metals and biotic materials (0.3 Mt), more than 54 million tons of material would not have to be extracted due to transport modal shift and low-carbon vehicle stocks. This amount is likely to increase, if technological development and recycling lead to better material efficiency.

For metal ores, the negative impact is dominated by EEIs in the personal transport sector. Considering both use and production of vehicles, an extra of 28 million tons of metal ores are required to be extracted in 2030 alone. This demand mainly stems from car production, which is only partially compensated for by their use and a modal shift. The resulting extra annual net demand for metal ores (28.4 million tons) is divided into the following ore types: an extra of 12.0 Mt for semi-precious metals, 9.1 Mt for precious metals, 11.7 Mt for other metals (mainly lithium) and savings of 4.6 Mt for ferrous metals. The direct input (metal) for copper amounts to 150,000 tons, for lithium carbonates to 103,000 tons, and for gold to 12 tons per annum. With the exception of lithium, none of this demand is deemed crucial on its own or from a low-carbon transport sector alone. Nonetheless, the occurrence of future supply bottlenecks for these metals in particular also depend on the metal ore demand in other areas, as a short literature review showed.

The authors applied a bottom-up approach by calculating the effects of over 20 different energy efficiency actions in different sectors all over Europe and summing these effects up. The models did not account for the fact that recycling rates for metals might increase due to policies for recovery. They also exclude assumptions on technological developments leading to higher material efficiency. Positive synergies can also be created by developing different sectors together, reducing environmental impacts as a consequence (e.g., by power-to-x technologies). Due to the focus on material resources, many environmental effects could not be accounted for. Deep and large structural changes for an energy-efficient Europe might harm water resources, induce land-use change, decrease biodiversity as well as generate additional waste or emit additional harmful substances into water, air and land. It is up to further research to determine whether all of these effects are going to be negative or whether positive effects occur in Europe alone.

The perspective applied in this study is driven from a technological and economic point of view. Societies invest in energy-efficiency products in Europe in order to meet the goals of a low-carbon society. It is recommended to validate these and similar findings by applying a more transdisciplinary approach which also takes into account the needs of future societies or the cultural drivers of transformation (e.g., as shown by [62]).

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Enough Metals? Resource Constraints to Supply a Fully Renewable Energy System

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Abstract: The transition from a fossil fuel base to a renewable energy system relies on materials and, in particular, metals to manufacture and maintain energy conversion technologies. Supply constraints shift from fossil fuels to mineral resources. We assess the availability of metal reserves and resources to build an energy system based exclusively on renewable energy technologies. A mass balance of 29 metals embodied in renewable energy technologies is compiled in order to satisfy global energy demand, based on five authoritative energy scenarios for 2050. We expand upon these scenarios by modeling the storage capacity needed to support high shares of intermittent renewables (wind and solar). The metal requirements are then compared with the current demand and proven reserves and ultimate mineable resources. This allows us to distinguish between constraints related to renewable energy sources from those linked to technology mixes. The results show that proven reserves and, in specific cases, resources of several metals are insufficient to build a renewable energy system at the predicted level of global energy demand by 2050. The comparison between reserves and resources shows that scarcity relates sometimes more to techno economic supply than to raw material availability. Our results also highlight the importance of substitution among technologies and metals as well as the limited impact of recycling on the depletion of scarce metals.

Keywords: global renewable energy system; metal reserves; supply side; storage; long-term scenarios

1. Introduction

The current energy system relies overwhelmingly on fossil fuels, with the associated combustion technologies and storage facilities. A very different system, based on renewable energy sources, must be built by 2050 to drastically reduce carbon emissions and avert catastrophic climate change [1]. Renewable energy (RE) sources, including solar, wind, hydropower, geothermal energy, and biomass, must be converted by renewable energy technologies to cover the final energy demand for heating and transportation fuels, as well as for electricity. These RE technologies have to be manufactured and maintained, which requires a flow and stock of mineral resources and, in particular, metals. In other words, attention is shifting away from oil, gas and coal reserves, which need to stay in the ground, to the reserves of metals required in the transition to a low carbon energy system [2–4].

Reserves are what can be extracted economically with current technology and available energy. Resources are the amount of ore known (proven, probable or potential) in the Earth's crust which become available as technology and prices evolve. This means that future reserves are found in today's resources, but changes in the energy cost of extraction for example, could also mean that current reserves become future resources [5]. The number of elements utilized by human activities has grown sharply, in particular for transition metals for manufacturing electronics and RE technologies [6].

Thus, the transition towards a fully renewable energy system places additional pressure on the main mineral resources, as well as on specialty metals [7–9]. However, unlike fossil fuels which are chemically degraded by combustion in the current energy system, metals in RE technologies retain their properties and can in principle be recycled. This offers greater potential for a circular economy, provided sufficient metal resources are available to build this new energy system. A lot of research already exists on the metal stocks and flows associated with new technologies including renewable energy ones [7,10–18]. However, none address the issue of metal scarcity from a comprehensive perspective, that is, by comparing jointly the global demand from industry to reserves and resources of the main and specialty metals for multiple RE technologies. Among the key attempts, Kleijn et al. [19] and Vidal et al. [20] assessed the material and mineral implications of switching from fossil fuels to low carbon technologies. While their results show that low-carbon sources of electricity require more metals and minerals, they did not compare this growing demand with current reserves and resources. Similarly, Vesborg and Jaramillo [21] estimated the volume of metals required to generate one TWh of final energy from a range of clean energy technologies without addressing scarcity or future energy demand.

The supply of metals depends on specific geological, physical and industrial conditions, such that one metric of supply does not fit all metals. Thus, supply constraints are often performed individually and per application, such as cadmium (Cd), tellurium (Te), indium (In), gallium (Ga) or selenium (Se) for thin film solar cells like cadmium–telluride (CdTe) or copper–indium–gallium–selenide (CIGS) [22–25]. In addition, the supply of these metals depends to a large extent on the extraction of parent metals such as copper, zinc, tin or aluminum and must be evaluated as such [26–28].

On the demand side, Kavlak et al. [29] quantified the metal requirements for large scale deployment of photovoltaics (PVs) according to energy scenarios, as well as from historical production/consumption of the different metals found in PV panels. They conclude that demand for indium, selenium and tellurium might limit the thin film PV industry as early as 2030. Grandell and Thorenz [30] reached a similar conclusion for silver (Ag). The availability of dysprosium (Dy) might also hinder the manufacturing of permanent magnets for wind turbines [17]. More generally, Harmsen et al. [31] evaluated the potential scarcity of copper (Cu) for long term global renewable energy scenarios (2050). Similarly, Elshkaki [32] concluded through dynamic material flow analysis, that resources of platinum (Pt) would be depleted before the end of this century. The supply of other metals such as cobalt (Co) [33] and lead (Pb) [34] might be less affected because they are recoverable from multiple sources.

Among the most comprehensive evaluations of metal use for RE technologies, Elshkaki and Graedel [11] quantified the availability of different metals used for wind turbines, PV panels, concentrated solar power (CSP), hydropower, geothermal, biomass, coal, oil, gas, and nuclear power under policy and market-based scenarios for 2050. They conclude that the manufacturing and replacement of wind turbines may not face major resource constraints, whereas the production of PV panels is potentially more problematic. Tellurium in particular might become critical in terms of resource availability and production capacity for CdTe panels. Yet, this study falls short of accounting for the metal constraint of a fully renewable energy system and excludes an important subset of metals, the platinum group metals (PGMs), which might prove critical.

We build on the work of Vidal et al. [7,20] and Habib et al. [35] who estimated the demand for main metals and rare earths respectively, in several renewable energy scenarios. We systematically estimate the demand for a set of 29 metals necessary for manufacturing and replacing RE technologies. Moreover, we use well established scenarios of energy supply and demand for 2050 which rely on 100% renewable energy sources, or with a small share of non-renewables. We also estimate the short-term storage requirements of intermittent sources, namely PV and wind, and account for the necessary battery technologies. Finally, we simulate different combinations of renewable energy and battery storage technologies to estimate the impact of the technology mix on metal scarcity. We then evaluate the metal scarcity by comparing the requirements for these scenarios and technology mixes with current extraction rates as well as current reserves and ultimate mineable resources. To evaluate the relative supply constraints of each metal, we compute their respective depletion horizon in terms of reserves and resources by considering the demand from both energy and non-energy industries. However, we focus exclusively on the energy supply side of energy-related activities, although the evolution of energy demand side technologies, such as electric vehicles, necessarily influence the demand for metals as well. We assume that the supply chains of metals are equally global as that of oil and gas, with potentially new cartels and regional disparities in resource supply [4,36]. In this sense, our results are based on a mass balance analysis, comparing supply and demand volumes, without addressing economic issues.

This comprehensive evaluation of the availability of energy metals is organized as follows: Section 2 details the methodological approach. In Section 3, we present our results and the impacts of energy and technology scenarios. Section 4 discusses these results and we conclude in Section 5.

2. Materials and Methods

To evaluate the potential supply constraints of metals, we estimate depletion horizons, or the year when reserves and resources would be depleted, should the deployment of a global and fully renewable energy system take place. While reserves and resources of metals are regularly re-evaluated alongside extraction, depletion horizon provides a common measure of scarcity. We consider the main renewable energy technologies as well as the stationary batteries needed to balance electricity generation from intermittent renewables (wind and solar). Although battery electric vehicles can also store electricity temporarily, in their first or second life, we ignore this possibility for now [37]. In order to estimate the extent to which the demand from renewable energy industries will impact the extraction of metals, we include the current demand from incumbent economic activities, such as electronics and aerospace which compete for the same metals.

Metal scarcity can be defined as follows: A steady decrease in the global average grade of ores extracted over time and an increase in prices of extracted metals which cannot be compensated by improving and upgrading mining technologies [38]. Improvements in mining technologies compensate for declining ore grades, but the energy cost of extraction keeps growing, with potential impacts on renewables [39]. Thus, we model different technology mixes for photovoltaics, wind, biomass, and storage technologies to assess substitution opportunities for the renewable energy industry. Five different battery chemistries were taken into account for intraday electricity storage.

The methodological approach can be divided into four steps. First we select five scenarios of global energy supply or demand in 2050, broken down by energy sources. These scenarios account for changes in demand for energy as a result of population and economic growth as well as energy efficiency and subject to the potential of renewable sources. Second, we integrate sub-scenarios of renewable energy technologies including solar PV and battery chemistries for storage. Third, we quantify the amount of each metal needed to manufacture and maintain renewable energy technologies in each of the five scenarios by taking the life cycle inventory of each technology and metal (kg/kWh) and scaling the metal requirements according to each scenario. We ignore potential resource productivity gains, as the rate of changes required in the energy system to meet emissions targets by 2050 will likely outpace productivity. In the fourth and last step, we compare the annual demand for metal with reserves and resources, assuming a renewable energy system is deployed linearly by 2050. Although recycling has little impact as demand grows and the energy system is implemented, we nonetheless included several recycling scenarios. Indeed, PV technologies for example have already witnessed their first lifecycle.

2.1. Energy Scenarios

Two well-established scenarios attempt to estimate global energy demand based exclusively on renewables: an IPCC scenario and one that results from the work of Ecofys and WWF [40,41]. We also include three scenarios with a high share of renewables: the International Energy Agency's "High RE" and "2 degree" scenarios, as well as the International Renewable Energy Agency (IRENA) "REMAP" scenario [42,43]. All of them have the same time horizon of 2050 but different estimates of global energy demand. They also differ on the share of each renewable (and non-renewable) energy source, such that they provide a measure of uncertainty in the energy supply and demand and the metals required to manufacture and maintain renewable energy technologies (see Figure 1).

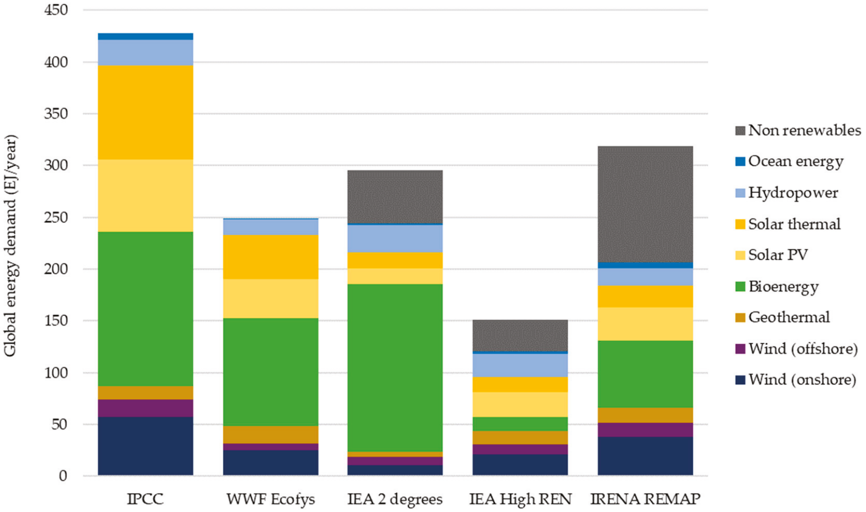

Figure 1. Five scenarios of global energy supply/demand in 2050 with high shares of renewables.

2.2. Renewable Energy Technology Scenarios

The scenarios in Figure 1 estimate global energy demand in 2050 together with supply per energy source. Forecasting the mix of technologies per energy source, such as that of PV technologies, is challenging not only because technology improves continuously but more importantly because a range of technologies normally co-exist, in particular for solar, wind, biomass or battery storage. Given the metals needed to manufacture each technology, the mixes require different quantities and often also qualities of metals. Thus, we used sub-scenarios of renewable energy technologies for solar PV, biofuels and battery energy storage as explained below. All scenarios already accounted for the potential of onshore and offshore wind power.

2.2.1. Solar PV Scenarios

The current market for photovoltaic (PV) panels is dominated by mono- and multi-crystalline silicon solar cells for which life cycle inventory (LCI) data exists [44]. IRENA forecasts that market shares of second generation thin film solar cells (CdTe, CIGS) will slowly increase to make up approximately 10% of the market in 2030 [45]. Thus, the PV technology mix here includes close to 90% of crystalline silicon, with multi-layered panels accounting for two-thirds. The remainder is split approximately equally between CdTe and CIGS technologies for which data also came from the ecoinvent LCI database [46]. In these inventories, the lifetime of PV panels are approximately 30 years. Thus, we concentrate on commercial PV technologies and do not consider future technologies such as Perovskites given the uncertainty regarding their deployment.

2.2.2. Biofuels

We consider second generation biofuels and the corresponding LCI data is relatively well documented. Although the impact of biomass would have to be regionalized, we only consider the metal requirements, especially catalysts, for biorefinery processes and no regional disparities. The use of biogas for transportation remains marginal and a mix of biodiesel and ethanol dominate the market [47]. In Figure 1, energy from biomass, including biofuels and the generation of heat and electricity are aggregated into a single category.

2.2.3. Storage Technologies

Intermittent renewable energy sources, namely solar and wind, require some forms of storage to balance supply and demand. The need for storage technologies increases non-linearly with the penetration of intermittent renewables. Many storage technologies, including batteries, also require specialty metals [48]. In Europe, the electricity surplus from renewable energy sources (approximately 40 TWh per year) is either curtailed, sold to neighboring countries or stored in pumped hydro and storage (PHS) plants [49]. Storage clearly depends on regional potential and installed capacity of solar and wind, as well as on the level of flexibility of the electric system (power plants, transportation grid, demand response). Therefore, in order to estimate the storage requirements regionally and globally, we derived the daily solar and wind profiles as well as the loads of five regions (EU, US, India, Brazil, and South Africa), representative of the five continents over a full year [50,51]. India represents Asia Pacific on its own for the lack of open data to model such profiles for China. Storage requirements were estimated by the daily surplus of renewable electricity in each region. The regionalized versions of the scenarios in Figure 1 were then used to scale up these storage requirements. We only considered intraday electricity storage, which can itself be covered by several technologies, centralized and decentralized [52]. We assumed that 50% of this storage would be covered by decentralized batteries and simulated three different mixes of five battery chemistries, including one non-lithium technology, for which LCI data is available [46,53,54] (see Appendix A for details). The estimated global storage requirements per scenario are given in Figure 2. For comparison purposes, we also show other estimates by IRENA, the Energy Watch Group and the World Bank [3,43,55].

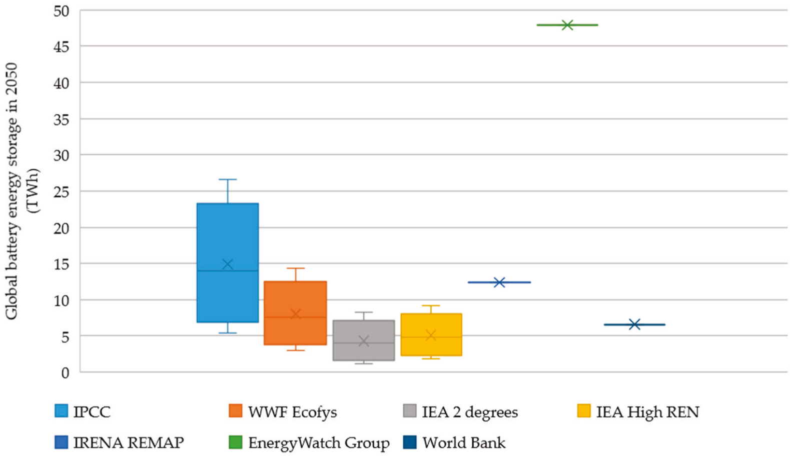

Figure 2. Storage requirements corresponding to energy scenarios and compared with 3 existing estimates.

2.3. Metal Inventory of Renewable Energy Technologies

The metals embodied in each renewable energy technology were quantified based on a life cycle perspective. In life cycle inventory (LCI) or impact assessment (LCIA), products (goods and services) are modeled with respect to their functions and measured by a functional unit. In the case of RE technologies, the functional unit is 1 kWh, such that LCI data sets provide the life cycle metal requirements per kWh. Data sets were sourced from the ecoinvent LCI database version 3 [46] which inventories 29 metals found in RE technologies (as shown in Figure 3). The data sets are so called "cradle to gate", meaning they account not only for the metals in the technology itself, but also those used for its manufacturing, installation, end of life, as well as its connection to the closest point of distribution (e.g., connection to the grid for wind turbines and PV panels) over the lifetime of the technology. Thus, we used intensities in kg of metal per functional unit and technology before scaling to the global energy system using the energy and technology scenarios above. For technologies that are not available in the ecoinvent database (e.g., emerging battery chemistries), we estimate their metal inventory based on literature references [48,53,56,57]. The metal intensity of each technology is summarized in Appendix B and details are available in supplementary data [58].

2.4. Metal Demand, Reserves and Resources

We model the energy system in 2050 and assume, for the sake of simplicity, a linear rate of deployment of RE technologies between 2017 and 2050. The model is not dynamic and targets the state of the energy system in 2050. To emphasize the growing demand for metals from RE technologies, we compare it with the aggregate demand from incumbent industries, which we assume to remain constant. In other words, we assume that high productivity gains for specialty metals in non-energy applications will offset part of the growth in demand. We also test the sensitivity of recycling rates, using four different recycling scenarios: (1) Current recycling rates for each metal remain unchanged for 2050 (conservative estimate) [59]. (2) A moderate 5% increase in recycling rates for each metal, between now and 2050, and (3) a more aggressive 50% increase is applied uniformly. (4) Specialty metals are recycled at the current rates of their parent metals, which are assumed to remain unchanged for 2050 (as in scenario 1), according to the wheel of metals by product [60,61]. A list of recycling rates for each metal and scenario is available in Appendix C.

The demand for metals from both the deployment of renewables and incumbent activities is then compared to the current reserves and resources reported by the US Geological Survey (USGS) [62]. The USGS defines *resources* as the “concentration of naturally occurring solid, liquid, or gaseous material in or on the Earth’s crust in such form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible”. *Reserves* refer to “that part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices, including those for grade, quality, thickness, and depth”. Where USGS estimates are aggregated for rare earths and PGMs, we disaggregate by metal based on the literature [18]. The difference between reserve and resource estimates illustrate some of the technical and economic constraints in bringing metals to markets which may stimulate material or technology substitutions.

Finally, we compute the ratio of reserves, respectively resources, over total demand up to 2050 measured by the sum of the growing demand from renewable energy technologies and the current demand from incumbent industries. Recycling simply reduces total demand, as in open loop recycling rather than displacing the demand for primary sources from renewable energy itself. The results yield a depletion horizon for each of the 29 metals and five scenarios. The demands from energy and technology scenarios translate into ranges of depletion horizons per metal and provide a measure of uncertainty.

3. Results

The results show that some metals are sufficiently scarce to set limits to the deployment of a fully renewable energy system before 2050. In this section, we present the results for reserve and resource depletion separately for comparison purposes, with the same mix of storage technologies including the five battery chemistries covering the average battery requirements, as shown in Figure 2. The current recycling rates are used and we then illustrate more specifically the impacts of recycling and storage scenarios for the scarcest of the metals. The corresponding cumulative metal demands are listed in Appendix D and the details are available in the Supplementary data.

3.1. Depletion Horizons of Metal Reserves

Figure 3 shows the ranges (in red) of depletion horizons for each metal across the five energy scenarios in Figure 1 if we were to deploy a fully renewable energy system by 2050. The black dots indicate the depletion years given the current demand alone, that is, without the deployment of a renewable energy system. For example, the ranges (in red) shift to the left of the depletion horizons for cadmium (Cd), cobalt (Co), lithium (Li) and Nickel (Ni) reserves, which indicates that renewable energy technologies will absorb a significant part of these metals in comparison with the demand from other, non-energy applications.

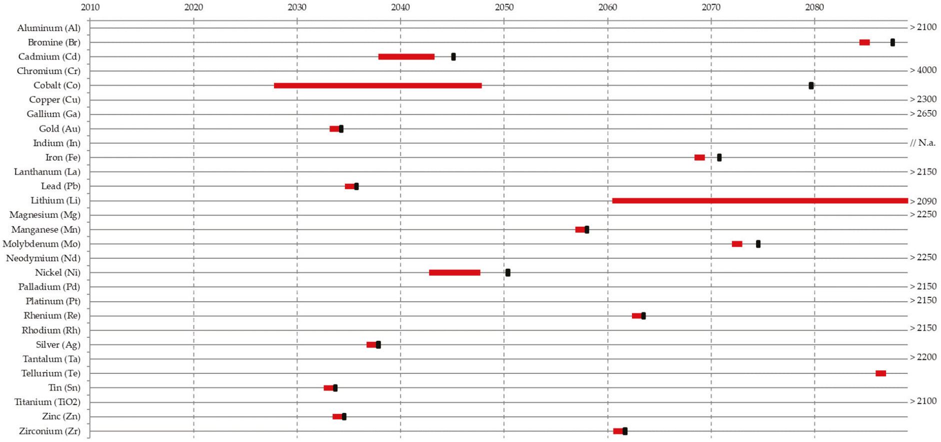

Figure 3. Depletion horizons based on reserves with demand from the energy sector (in red) ranging across energy scenarios and demand without the energy sector (in black). N.a. means no data available.

Figure 3 also shows that the reserves of eight metals (Cd, Co, Au, Pb, Ni, Ag, Sn, Zn) are likely to be depleted before a renewable energy system can be deployed on a large scale in 2050. This is irrespective of the energy or technology scenarios and the level of energy demand. The depletion ranges for Cd, Co and Ni are longer, meaning greater uncertainty. Lithium (Li) reserves also exhibit a long depletion range between 2060 and the end of the century, that depends on the energy and storage scenarios. It is important to note that for some of these scarce metals (Cd, Co, Li, Ni), the deployment of a renewable energy system moves the depletion horizons closer from that set by incumbent (non-energy) industries (red bars and black dots differ). Competition for these metals might thus become a reality in the coming decades between traditional and new energy industries.

Other metals fare better with a depletion horizon beyond 2100 and should not experience any foreseeable supply constraints. Unfortunately, reserve data is missing for indium (In) such that we cannot conclude at this stage. The cumulative metal demands underlying the results in Figure 3 (and Figure 4) are available in Appendix D.

3.2. Depletion Horizons of Metal Resources

Resources are more abundant than reserves by definition and less subject to techno-economic changes. Hence, resources represent a more absolute measure of scarcity than reserves. The difference with reserves essentially shows the challenge for exploration and exploitation technologies to respond to changes in demand. Figure 4 shows the depletion horizons based on resources for the 29 metals. It shows that five of them (Cd, Co, Li, Mo and Ni) are scarce in resource terms. Moreover, it is the additional demand from the deployment of renewables that makes a significant difference for Cd, Co, Li and Ni. Cd, Co and Li also exhibit long depletion ranges across scenarios which means substitution in generation and storage technologies might alleviate such problems.

Another two metals (Pb and Zn) were shown to be scarce based on reserves in Figure 3, but are relatively abundant in terms of resources. Thus, short-term constraints on the availability of these metals is mostly due to a market imbalance and might be addressed with exploration and advanced extraction technologies to align production capacities with demand in the medium term. Unfortunately, data on resources is missing for nine metals (Au, La, Mn, Nd, Ag, Ta, Te, Sn and Zr), several of which were identified as scarce based on reserves.

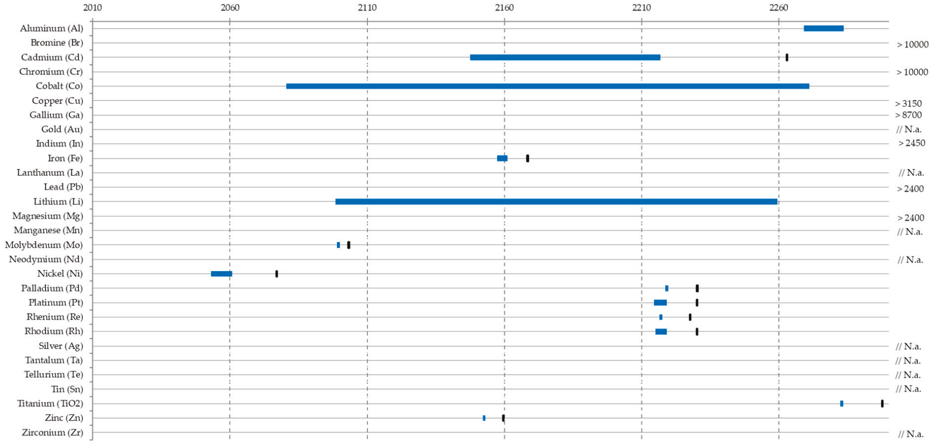

Figure 4. Depletion horizons based on resources with demand from the energy sector (in blue) ranging across energy scenarios and demand without the energy sector (in black). N.a. means no data available.

Although some metals are scarce, most of the available resources shown in Figure 4 can last well beyond our foreseeable future. In addition, the extended ranges (in blue) for some scarce metals suggest that substitutes are likely to be found before resource constraints arise. Besides substitution, technology scenarios also have an impact, in particular for storage and recycling as explained below.

3.3. Storage Scenarios

We assumed batteries to cover half of the intraday electricity storage requirements. Figure 5 shows how sensitive the metals, which reserves were identified as scarce, are to battery energy storage. In addition to the medium storage scenario accounted for in the results above, Figure 5 shows a high and low storage scenario, as well as the no battery energy storage option. The impacts of such storage scenarios proves to be negligible on the depletion horizon of most metals, with the exception of cobalt (Co), nickel (Ni), and most importantly lithium (Li). The depletion horizon of Li drops from 2360 without storage to between 2075 and 2060 depending on the storage scenario.

Thus, alternative centralized and decentralized storage technologies such as power-to-gas coupled with renewables, compressed air or flywheels, could defer potential constraints on metals for batteries. Demand response strategies might also lower the need for storage by aligning electricity demand with supply from intermittent renewables.

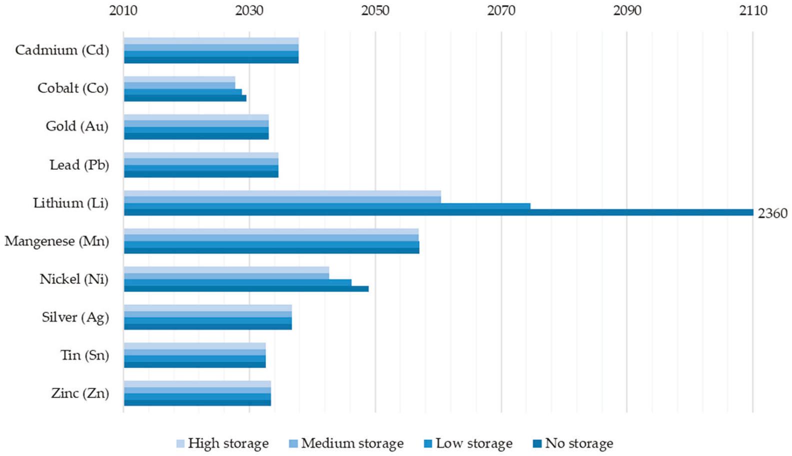

Figure 5. Depletion horizons based on reserves per storage scenario.

3.4. Recycling Scenarios

Similar to storage scenarios, changes in recycling rates have minimal impact on the depletion horizon of most metals. Figure 6 shows the impact of four distinct recycling scenarios: current recycling rates (which are used in the results above), a marginal 5% increment in recycling rates, a 50% increase in recycling rates and for specialty metals, a recycling rate comparable to that of their parent metals. For example, the global recycling rate of In currently stands at 1% but would increase to 50% in the case of parent metal Zn. For most specialty metals, the current recycling rates are extremely low, and even if they increased significantly, the stocks would not be sufficient to cover a significant share of the demand from recycling. Moreover, metals for which recycling rates are close to their maximum (e.g., Al, Fe, Cu, Au) are not only in high demand from incumbent industries, but they also have long residence times in use. The depletion horizon for iron (Fe), around 2070, might be surprising but stocks in use have already peaked in many OECD countries at 12 tons per capita [63]. At this stage, secondary steal becomes more economic than primary sources. Nevertheless, recycling scenarios make a difference for four key metals, Cd, Co, Li and Ni, as shown in Figure 6.

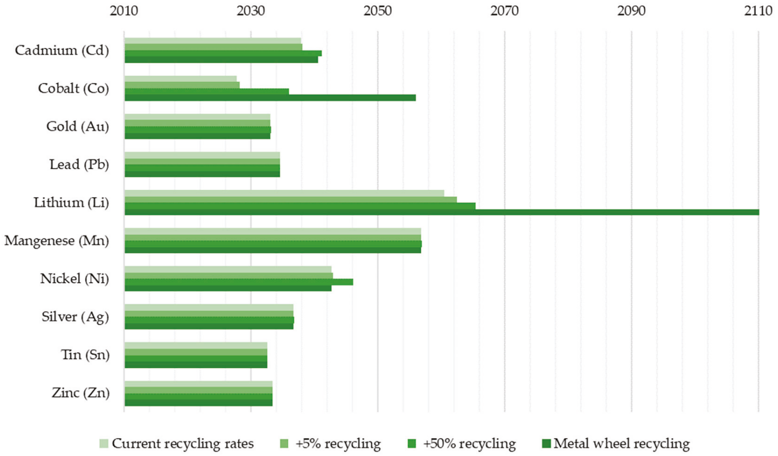

Figure 6. Depletion horizons based on reserves for each of the four recycling scenarios.

4. Discussion

In absolute terms, this analysis shows that although some metals are scarce, a fully renewable energy system is unlikely to deplete metal reserves and resources up to 2050. Metal productivity gains, as well as substitutions at the technology and metal levels, should become more viable technically and economically before the ore grades decline and the energy costs of extraction rise [39].

In this sense, our results are most relevant from a relative perspective, as they identify those metals that are likely to become scarce first, and thus, contribute to prioritizing R&D and industry efforts towards the substitutions of RE technologies or metals per se. Such alternatives can be at the expense of energy efficiency. For instance, asynchronous motors without permanent magnets in the rotors of wind turbines exist but are slightly less efficient than conventional motors. Similarly, replacing silver with copper as conductive elements in crystalline silicon solar cells would slightly reduce their conversion efficiency. Thus, the level of technological development and the global energy demand and technology scenarios determine whether future energy systems will be "high or low tech" and renewable energy scarce or abundant.

In the context of decarbonization to mitigate climate change, a fully renewable energy system could provide as much energy as we wanted, since its carbon intensity is significantly lower than the current fossil-fueled system. We show here that even if the energy system was fully renewable, supply constraints on several elements other than carbon would still compel us to reduce our energy demand. However, our analysis shows that shifting from a fossil-based to a RE-based system does not alleviate the problem of resource depletion, it merely shifts it from fuel to metal. The key difference between these two energy systems is that a RE-based system offers many alternative options when metal scarcity rises, such as substitution and recycling. In the list of priorities, we can start to reduce the cobalt intensity of energy technologies. Similar conclusions can be drawn from the results for cadmium and nickel. Equally important according to our results is the dependency of energy technologies on precious metals, in particular gold and silver. Stocks in use and recycling rates are high, but again, other uses are competing for them at a comparative advantage.

Intraday electricity storage with batteries has a significant impact on the usual suspects, cobalt, lithium and nickel. While storage itself compounds the impacts of renewable energy scenarios, alternatives to batteries exist. These alternatives would certainly not make batteries obsolete, but would lower their demand to a level which might be adequate with the availability of resources. Moreover, a large and well interconnected grid might reduce the problem of intermittency in sunny days followed by windy nights in different regions. Similarly, the minimal impact of recycling scenarios comes essentially from the fact that a global energy system has to be built over 30 to 40 years, not much longer than the typical lifetime of equipment. Therefore, a high recycling rate does not compensate for growth in demand for most metals, even iron which has one of the highest global recycling rates and stocks in use of all metals.

To our surprise, the results on depletion horizons do not change significantly when the global energy demand in 2050 varies from 120 EJ to 450 EJ of renewable energy (see Figure 1). The number of metals for which the range of uncertainty is large increases slightly from reserves to resources, which was expected, but remains small. This shows that the determining factor for depletion horizons is more how renewable energy sources are converted into useful energy, or the mix of RE technologies, rather than the energy scenarios themselves [64]. Our results may therefore prove particularly relevant in steering future applied research and development in line with material constraints over the medium and long term [65]. Concentrating our efforts towards material or technology substitutions is a priority since many alternatives which do not rely on scarce metals already exist.

Finally, our assessment focused exclusively on metals for supply-side technologies, neglecting metal requirements to manufacture demand-side technologies such as electric vehicles, fuel cells and energy efficiency measures. As part of the demand side, a more accurate assessment is also needed to account for the demand for specialty metals from non-energy industries. Moreover, what happens beyond 2050 in terms of maintenance of a fully renewable energy system is another important research question which remains open.

5. Conclusions

The objective of the research presented in this article is to perform a comprehensive assessment of metal supply constraints for a fully renewable energy system in 2050. Out of 29 necessary metals in the lifecycle of renewable energy technologies, the reserves of 8 metals might be depleted before then. However, the renewable energy industry would only mobilize a small additional share of the demand for specialty metals compared to the global demand from incumbent industries. The exceptions are Cd, Co, Li, and Ni, for which the depletion horizons vary across renewable energy scenarios. This is consistent with previous results [15,19]. However, the comparison between reserves and resources indicates where technical rather than geological bottlenecks might be alleviated through investments. In terms of resources, Cd, Co, Li and Ni also show the largest dependency on the demand of renewable energy systems.

We conclude that deploying an energy system based exclusively on renewables requires major changes to global energy demand and the development of appropriate technologies less reliant on specialty metals. While past research and development efforts have focused on improving the efficiency of energy conversion technologies (e.g., solar cells, wind turbines), which have generated a growing reliance on specialty metals, we might witness a side step to potentially less efficient technologies in the future in order to lower the risks of supply constraints. Whether future energy technologies will be high or low tech has great implications on resource depletion. Nevertheless, the fossil fuel equivalent of our remaining carbon budget would be wisely spent on the extraction of metals required for renewable energy technologies.

Author Contributions: Conceptualization, F.V. and V.M.; methodology, V.M.; validation, F.V. and P.C.D.R.; formal analysis, V.M., P.C.D.R.; data curation, P.C.D.R.; writing—original draft preparation, V.M.; writing—review and editing, F.V. and V.M.; visualization, P.C.D.R.; supervision, V.M. and F.V.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

The battery energy storage scenarios are reported below with a short description of each battery's chemistry. The battery storage capacity for each scenario was increased by 25% to account for cycling losses in charging and discharging.

NCA—Lithium nickel cobalt aluminium—is a battery cell consisting of a graphite anode, $LiNiCoAlO_2$ cathode and Lithium carbonate electrolyte. It has high energy density and good cycle life, but thermal stability is moderate [56].

NCM622—Lithium nickel manganese cobalt—is a battery cell consisting of a graphite anode, $LiNi_{0.6}Mn_{0.2}Co_{0.2}O_2$ cathode and Lithium carbonate electrolyte. NCM622 contains a higher nickel content than NCM111, which leads to higher energy density, decreased costs and lower thermal stability. Market diffusion is expected by 2020 [57].

NMC811—Lithium nickel manganese cobalt—is a battery cell consisting of graphite + silicon anode, $LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$ cathode and Lithium carbonate electrolyte. The presence of small quantities of silicon in the anode increase the energy intensity. This next generation technology is currently under R&D and is expected to diffuse by 2025 [57].

LFP—Lithium iron phosphate—is a battery cell consisting of a graphite anode, $LiFePO_4$ cathode and Lithium carbonate electrolyte. It has high cycling life and safety parameters at low costs. However, its energy density is low [56].

Zebra NaNiCl—high temperature Sodium Nickel Chloride Battery—is a sodium metal halide battery designed to operate under high temperatures (>270 °C) and for long periods of discharge (≥6 h). LCI data was sourced from ecoinvent [46].

Table A1. Battery chemistries mixes.

2050	**MIX 1**	**MIX 2**	**MIX 3**
NCA	20%	25%	20%
NCM622	0%	5%	0%
NCM811	30%	45%	80%
Zebra (NaNiCl)	50%	10%	0%
LFP	0%	15%	0%

Appendix B

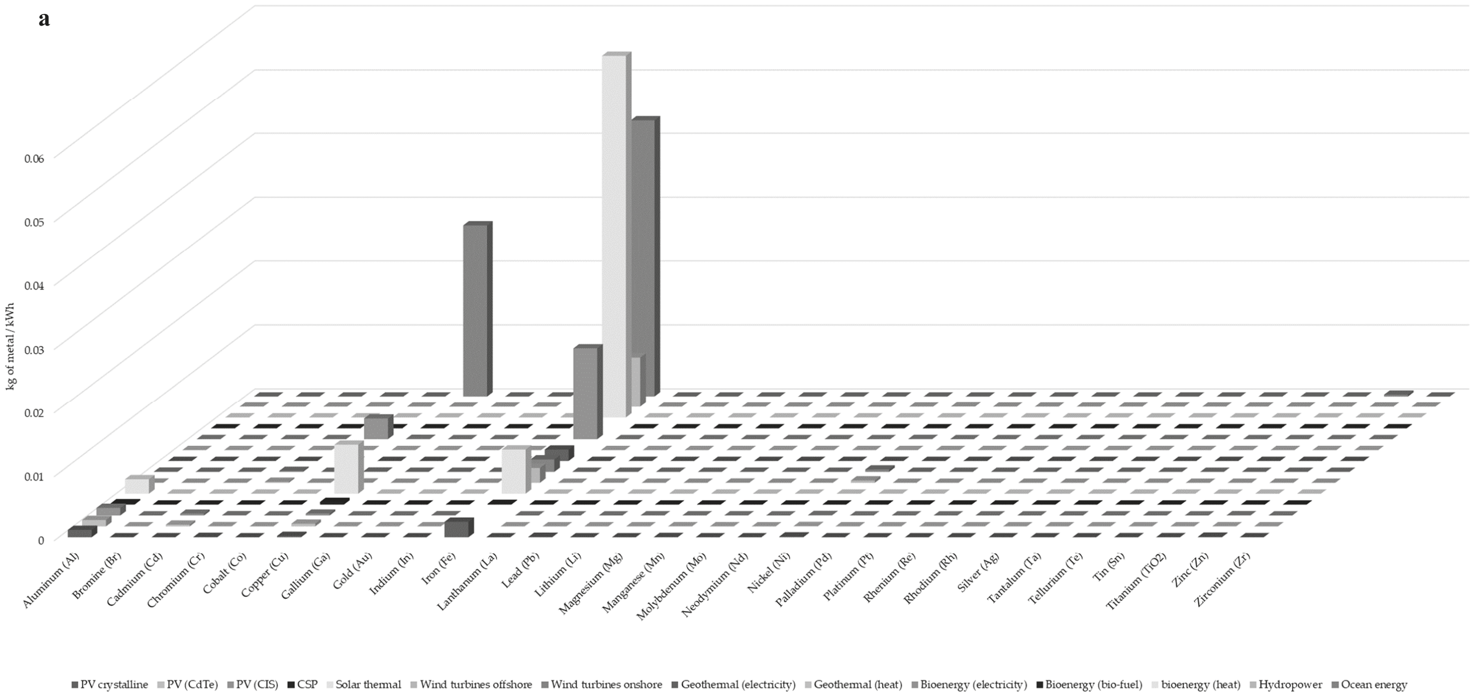

Figure A1. *Cont.*

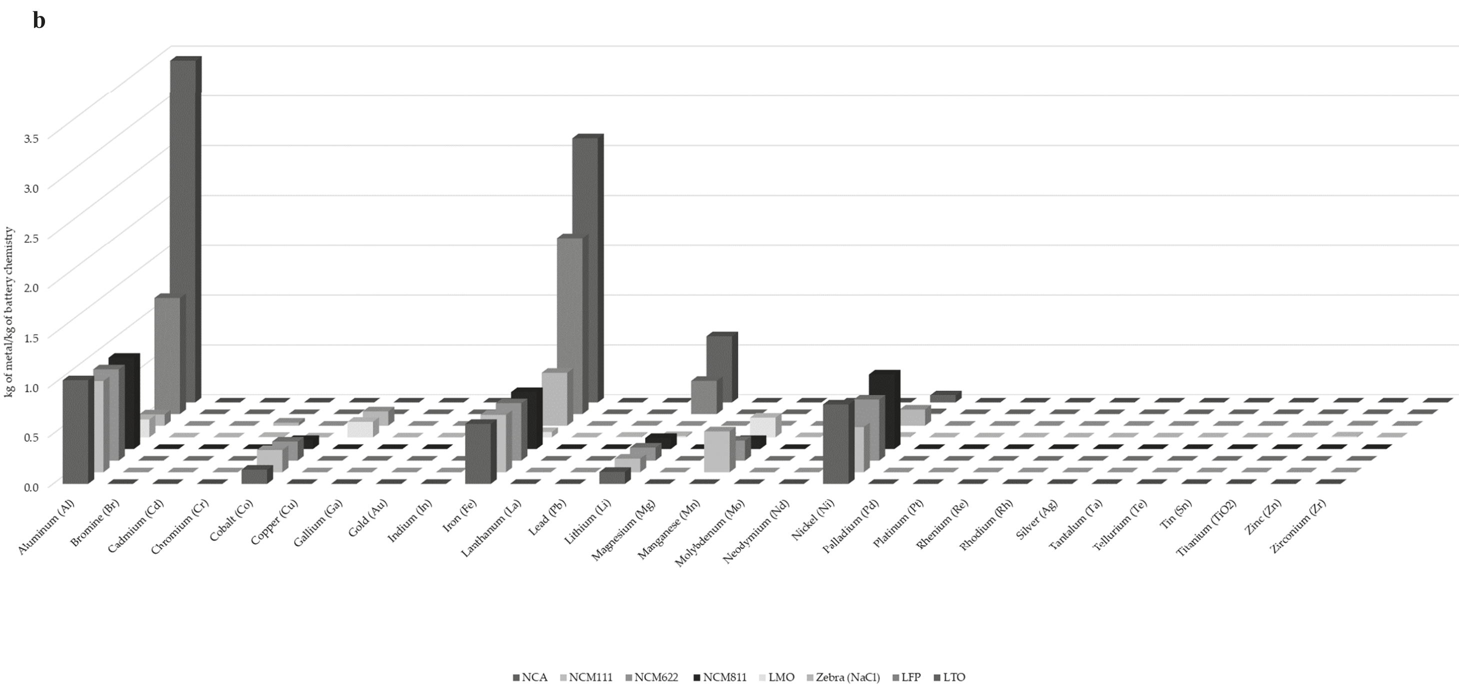

Figure A1. Metal intensities for RE technologies (**a**) and battery chemistries (**b**).

Appendix C

Table A2. Recycling scenarios.

	Current	+5%	+50%	Parent Metal
Aluminum (Al)	50%	53%	76%	50%
Bromine (Br)	1%	6%	53%	50%
Cadmium (Cd)	10%	15%	57%	50%
Chromium (Cr)	50%	53%	76%	50%
Cobalt (Co)	50%	53%	76%	94%
Copper (Cu)	50%	53%	76%	50%
Gallium (Ga)	1%	6%	53%	50%
Gold (Au)	50%	53%	76%	50%
Indium (In)	1%	6%	53%	50%
Iron (Fe)	50%	53%	76%	50%
Lanthanum (La)	1%	6%	53%	50%
Lead (Pb)	50%	53%	76%	50%
Lithium (Li)	1%	6%	53%	81%
Magnesium (Mg)	25%	29%	64%	25%
Manganese (Mn)	50%	53%	76%	50%
Molybdenum (Mo)	25%	29%	64%	25%
Neodymium (Nd)	1%	6%	53%	25%
Nickel (Ni)	50%	53%	76%	50%
Palladium (Pd)	50%	53%	76%	50%
Platinum (Pt)	50%	53%	76%	50%
Rhenium (Re)	50%	53%	76%	50%
Rhodium (Rh)	50%	53%	76%	50%
Silver (Ag)	50%	53%	76%	50%
Tantalum (Ta)	1%	6%	53%	50%
Tellurium (Te)	1%	6%	53%	50%
Tin (SN)	1%	6%	53%	50%
Titanium (TiO2)	50%	53%	76%	50%
Zinc (Zn)	50%	53%	76%	50%
Zirconium (Zr)	1%	6%	53%	25%

Appendix D

Table A3. Cumulative metal demand for the scenarios in Figures 3 and 4.

Metal	Cumulative production [Mt]	IPCC [Mt]	WWF [Mt]	IEA 2DS [Mt]	IEA High Ren [Mt]	IRENA REMAP [Mt]
Aluminum (Al)	2.2×10^3	1.7×10^2	9.4×10	4.6×10	5.2×10	1.3×10^2
Bromine (Br)	1.2×10	2.3×10^{-4}	1.2×10^{-4}	4.9×10^{-5}	7.9×10^{-5}	1.0×10^{-4}
Cadmium (Cd)	8.0×10^{-1}	6.3×10^{-1}	3.3×10^{-1}	1.3×10^{-1}	2.1×10^{-1}	2.8×10^{-1}
Chromium (Cr)	3.3×10^{-1}	4.5	2.0	1.2	1.8	2.7
Cobalt (Co)	3.8	7.1×10^1	2.1×10^1	1.6×10^1	1.5×10^1	1.5×10^1
Copper (Cu)	6.9×10^{-1}	1.5×10^2	5.7×10^1	3.2×10^1	1.8×10^1	7.8×10^1
Gallium (Ga)	1.7×10^{-2}	5.8×10^{-3}	3.1×10^{-3}	1.2×10^{-3}	2.0×10^{-3}	2.6×10^{-3}
Gold (Au)	1.1×10^{-1}	3.5×10^{-4}	1.8×10^{-4}	7.6×10^{-5}	1.2×10^{-4}	1.6×10^{-4}
Indium (In)	2.5×10^{-2}	4.7×10^{-2}	2.5×10^{-2}	1.0×10^{-2}	1.6×10^{-2}	2.1×10^{-2}
Iron (Fe)	5.2×10^4	1.2×10^3	8.4×10^2	1.5×10^3	1.9×10^2	9.0×10^2
Lanthanum (La)	1.2	1.6×10^{-4}	8.8×10^{-5}	3.5×10^{-5}	5.7×10^{-5}	7.5×10^{-5}
Lead (Pb)	1.6×10^2	1.0	5.5×10^{-1}	2.6×10^{-1}	3.9×10^{-1}	5.1×10^{-1}
Lithium (Li)	1.5	2.0×10	1.0×10	5.7	6.9	1.7×10
Magnesium (Mg)	5.7×10^2	1.5×10^{-2}	8.3×10^{-3}	3.4×10^{-3}	5.4×10^{-3}	7.1×10^{-3}
Manganese (Mn)	5.6×10^2	5.6	2.9	1.6	2.0	4.6

Table A3. *Cont.*

Metal	Cumulative production [Mt]	IPCC [Mt]	WWF [Mt]	IEA 2DS [Mt]	IEA High Ren [Mt]	IRENA REMAP [Mt]
Molybdenum (Mo)	1.0×10	6.6×10^{-2}	2.9×10^{-2}	1.6×10^{-2}	2.3×10^{-2}	3.1×10^{-2}
Neodymium (Nd)	8.1×10^{-1}	1.9×10^{-2}	7.8×10^{-3}	9.3×10^{-3}	1.1×10^{-2}	1.5×10^{-2}
Nickel (Ni)	7.3×10	8.5×10	4.5×10	2.4×10	3.0×10	7.2×10
Palladium (Pd)	7.7×10^{-3}	4.1×10^{-5}	1.1×10^{-5}	1.0×10^{-5}	7.9×10^{-6}	5.7×10^{-6}
Platinum (Pt)	7.1×10^{-3}	1.9×10^{-4}	5.3×10^{-5}	5.1×10^{-5}	3.5×10^{-5}	2.3×10^{-5}
Rhenium (Re)	1.8×10^{-3}	1.6×10^{-8}	7.3×10^{-9}	3.7×10^{-9}	4.8×10^{-9}	5.9×10^{-9}
Rhodium (Rh)	1.4×10^{-3}	3.3×10^{-5}	8.8×10^{-6}	8.8×10^{-6}	5.9×10^{-6}	3.7×10^{-6}
Silver (Ag)	8.7×10^{-1}	4.5×10^{-2}	2.2×10^{-2}	8.5×10^{-3}	1.4×10^{-2}	1.0×10^{-2}
Tantalum (Ta)	4.5×10^{-2}	5.6×10^{-3}	2.9×10^{-3}	1.2×10^{-3}	1.9×10^{-3}	2.5×10^{-3}
Tellurium (Te)	1.4×10^{-2}	1.4×10^{-4}	7.7×10^{-5}	3.1×10^{-5}	5.0×10^{-5}	6.5×10^{-5}
Tin (Sn)	1.0×10	3.3×10^{-2}	1.7×10^{-2}	7.3×10^{-3}	1.1×10^{-2}	1.4×10^{-2}
Titanium (TiO2)	2.4×10^{2}	2.3×10^{-1}	1.1×10^{-1}	5.3×10^{-2}	7.5×10^{-2}	9.8×10^{-2}
Zinc (Zn)	4.6×10^{2}	2.0	8.3×10^{-1}	4.7×10^{-1}	6.5×10^{-1}	1.1
Zirconium (Zr)	4.1×10	4.1×10^{-2}	2.2×10^{-2}	8.9×10^{-3}	1.4×10^{-2}	1.8×10^{-2}

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Devising Mineral Resource Supply Pathways to a Low-Carbon Electricity Generation by 2100

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Abstract: Achieving a "carbon neutral" world by 2100 or earlier in a context of economic growth implies a drastic and profound transformation of the way energy is supplied and consumed in our societies. In this paper, we use life-cycle inventories of electricity-generating technologies and an integrated assessment model (TIMES Integrated Assessment Model) to project the global raw material requirements in two scenarios: a second shared socioeconomic pathway baseline, and a 2 °C scenario by 2100. Material usage reported in the life-cycle inventories is distributed into three phases, namely construction, operation, and decommissioning. Material supply dynamics and the impact of the 2 °C warming limit are quantified for three raw fossil fuels and forty-eight metallic and nonmetallic mineral resources. Depending on the time horizon, graphite, sand, sulfur, borates, aluminum, chromium, nickel, silver, gold, rare earth elements or their substitutes could face a sharp increase in usage as a result of a massive installation of low-carbon technologies. Ignoring nonfuel resource availability and value in deep decarbonation, circular economy, or decoupling scenarios can potentially generate misleading, contradictory, or unachievable climate policies.

Keywords: industrial ecology; integrated assessment models; life-cycle inventories; mineral resources; decoupling; prospective scenario analysis; TIAM-FR; socioeconomic metabolism

1. Introduction

According to the Intergovernmental Panel on Climate Change (IPCC), limiting global warming to 2 °C is possible on the condition of a drastic reduction in greenhouse gas emissions (GHGs) [1]. One of the most effective mitigation actions consists of reshaping the energy system with energy processes that produce fewer or negative CO_2 emissions. Such a transformation requires energy and materials, which translates into tensions over natural assets—namely space (land, air, oceans) and material resources. Integrated assessment models (IAMs) are tools that explore the interactions between the environment and socioeconomic spheres. These tools produce scenarios that are used by policymakers to plan GHG mitigation actions while minimizing socioeconomic costs. Nonfuel mineral resources are typically not considered in IAMs [2,3], seemingly due to their apparent non-energy or non-GHG-related nature. However, nonfuel resources constitute every product in the technosphere. They are necessary to build new low-carbon infrastructures and technologies to maintain or improve living conditions while mitigating global warming. Raw materials are often exploited unsustainably and their processing chains can involve significant environmental impacts [4]. Thus, socioeconomic development, energy consumption, and environmental impacts are strongly related to resource usage.

Different approaches exist to project the future material requirements of specific regions, sectors, or technologies depending on an evolving environment. A common approach—focusing on material demand—is to combine data on material usage with development scenarios employing evolution-characteristic parameters such as population growth, monetary flows, energy produced, additional number of products, etc. [5–15]. Data on material usage might only include direct "consumption" by processes or material content in products. In this case, potentially large material requirements in the supply chain of a process can be omitted. To address this issue, some authors have used life-cycle inventory (LCI) data, which include indirect consumption generated by the upstream and downstream activities of processes [16,17]. In particular, this approach has been successfully demonstrated on low-carbon technologies to project the consumption of iron, aluminum, copper, and cement according to the International Energy Agency's (IEA's) decarbonation scenario (BLUE Map) [18] by 2050. However, a global bottom-up study covering the full mineral resource footprint of energy needs has never been made to our knowledge.

In order to investigate the consumption of all substances found in the life cycles of electricity-generating (EG) technologies, we introduced an original method [19] to combine life-cycle inventories (LCIs) with the electricity outputs of the TIMES integrated assessment model (TIAM-FR). This method used ecoinvent 3.3, one of the most complete process LCI databases. The growing number of datasets contained in ecoinvent result from life-cycle assessments (LCAs) performed by different authors in order to compare the environmental impacts of given activities and products. Each activity has its material and energy inputs and outputs reported. The calculation of an LCI gives a list of substances, the usage of which the activity is responsible for. Here, we take the same approach to assess the mineral resource use of EG technologies along two scenarios: a second shared socioeconomic pathway (SSP2) baseline [20] and a 2 °C target scenario. We set out to analyze and compare the dynamic material requirements of three groups of raw fossil fuels and forty-eight groups of mineral resources during the construction, operation, and decommissioning of each power plant in 15 world regions. We present three main types of result: First, we project the requirements of fossil fuels and metallic and nonmetallic mineral resources in both scenarios. Second, we analyze each substance individually, calculating its increasing or decreasing usage relative to the 2020 decade, as well as the decade-to-decade increase or decrease in its usage. Third, we calculate the ratio between the 2 °C and baseline scenarios for each time period, to quantify the relative difference of resource usage due to the 2 °C target. In particular, we focus on the five substances showing the highest values of each indicator, depending on the time period.

This prospective LCI approach to global electricity generation provides important insights into the link between decarbonation scenarios, climate targets and mineral resource requirement pathways.

2. Method

2.1. TIAM-FR Model

TIAM is a bottom-up optimization model pertaining to the TIMES family. It was developed by the Energy Technology Systems Analysis Program (ETSAP) group of the International Energy Agency (IEA) in order to provide global energy scenarios with emission mitigation targets. TIAM-FR is the version of TIAM developed at MINES ParisTech Center for Applied Mathematics. In each of the 15 world regions considered (see Supplementary Table S1 for a list of regions and their acronyms), TIAM-FR establishes a balance between a set of demand drivers (population, economic growth, energy, and service needs) and supply technologies (fuel, electricity, transportation, etc.) distributed in five sectors (agriculture, commercial, industry, residential, and transportation). 2010 is taken as a reference year for which the system's state is entirely and exogenously defined. The 2010–2100 horizon is divided in 11 periods. An optimization algorithm minimizes the total net present value of the total annual cost, discounted at 5% to the selected reference year 2010. A full description of the TIAM model is available publicly [21,22]. Most technology costs and data are freely accessible from the ETSAP community's website [23]. Some cost data were obtained from experts or manufacturers. Production, trade, consumption, and socioeconomic data were obtained from international institutions (e.g., FAO, World Bank, etc.). Energy data were purchased at IEA's data services when they were not freely accessible. TIAM-FR has been previously used for global and regional analyses [24] and water consumption assessments [25], and was recently updated with a detailed bioenergy sector [26,27] including carbon capture and sequestration (CCS) technologies. Using TIAM-FR, we determine a baseline scenario that is comparable to a second shared socioeconomic pathway (SSP2) [20]. The assumptions regarding population and gross domestic product growth for each region were previously reported in the Supplementary Material of [19]. From the baseline scenario, a 2 °C scenario is obtained by setting a maximum global warming target of 2 °C by 2100 (with an overshoot tolerance of 0.1 °C). GHG emissions, total primary energy supply, and total final consumption are reported in the Supplementary Material of the present article. The SSP2 baseline scenario is in agreement with primary supply, final consumption, and GHG emissions found in the literature [28,29].

2.2. Linking Electricity Outputs with Life-Cycle Inventories

We compute material usage scenarios for EG technologies using a method previously described [19]. It is based on the combination of the TIAM-FR electric outputs and life-cycle inventories of EG technologies. Each of the 109 EG technologies in the TIAM-FR model is attributed a process-based LCI extracted from the ecoinvent 3.3 database. We deliberately choose not to use other sources of LCI datasets to keep the consistency provided by ecoinvent. Indeed, each life-cycle inventory in ecoinvent was built from elementary processes, which can be traced back through the entire processing chain. For the TIAM-FR technologies that are not represented in ecoinvent (e.g., marine and CCS technologies), we select alternative datasets in a close technological family. This approximation adds a layer of uncertainty; however, it allows us to cover all electricity generation. In the future, the increasing number of technologies analyzed in ecoinvent will help reduce the recourse to such approximations. Potential recycled materials are taken into account using ecoinvent's "at the point of substitution" (APOS) system linking method. This method expands the technology's system boundaries to include waste treatment activities. For all datasets, we separate infrastructure activities from transformation activities, which allows us to distinguish the material consumption during the construction, operation, and decommissioning phases. We allocate 90% of the infrastructure LCI to the construction phase and 10% to the decommissioning phase as described in [19]. The transformation LCI is allocated to the power plant operation phase. We study all raw fossil fuels and mineral resources that are extracted from the ground as defined in ecoinvent. Water, biomass, and non-energy gases are not considered in this study. The material use results are represented in 16 energy source categories: bioenergy, bioenergy with CCS, coal, coal with CCS, coal–bioenergy cofiring, coal–bioenergy cofiring with CCS, gas, gas with CCS, geothermal, hydro, marine, nuclear, oil, solar photovoltaics (PV), solar thermal, and wind.

3. Results

3.1. Global Electricity Generation

Global greenhouse gas emissions, primary energy supply, and final consumption are described in the Supplementary Materials (Figures S1, S2, and S3). The evolution of the power mix associated with the SSP2 baseline and 2 °C scenarios towards 2100 is represented in Figure 1. Three outputs are shown: the annual new capacities, electricity production, and end-of-life capacities of EG technologies. Global electricity production reaches 233 EJ/year in the 2 °C scenario in 2100, 13 EJ/year higher than in the baseline scenario. However, the way electricity is produced in the 2 °C scenario significantly differs from the baseline after 2040.

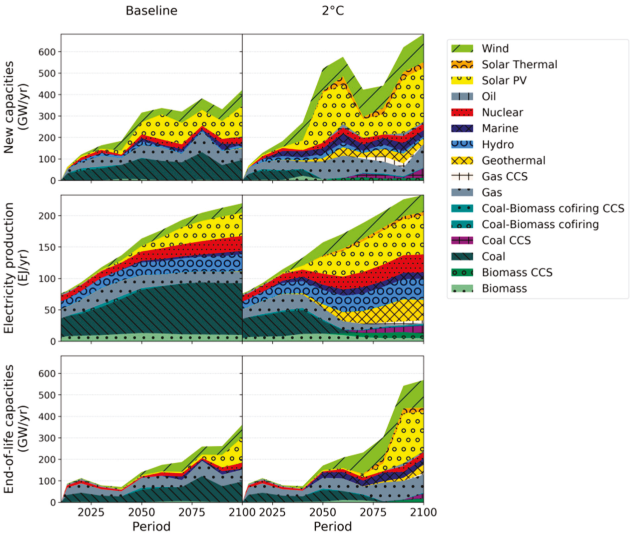

Figure 1. Annual new capacities, electricity production, and end-of-life capacities of electricity-generating technologies, in the baseline scenario (left) and 2 °C scenario (right). CCS: With carbon capture and sequestration technologies. Data are found in Supplementary Material (Table S2).

In the baseline scenario, electricity production is mostly coal-based and remains so until the end of the century. Coal is the major contributor to the increasing electricity supply until 2060, when wind and solar capacities take over to fulfill 23.6% of global electricity generation by 2100. In both scenarios, electricity production follows a similar trend until 2030 when, in the 2 °C scenario, coal and gas electricity production peak at 39 EJ/year and 25 EJ/year, respectively. After 2030, solar and wind capacities are increasingly installed as lower GHG emissions are needed to reduce the total system's cost. Conventional coal capacities are phased out by 2070. Solar photovoltaics (PV) becomes the leading electricity producer, reaching 27 EJ/year in 2050. During the 2040–2050 period, up to 200 GW/year of solar PV and 90 GW/year of wind capacities are added to the world grid to limit global warming to 2 °C by 2100. 30 GW/year of natural gas power plants are installed concurrently as backups (intermittent power capacities are limited to 50% of total capacities in the TIAM-FR model). Hydropower, nuclear, and geothermal capacities develop in the 2 °C scenario to production levels of about 30 EJ/year in 2100. After a transition phase occurring between 2030 and 2060, electricity generation from solar PV increases slowly and fewer additional solar capacities are needed. Wind farms are still added to the grid to compensate for the massive end-of-life wind capacities observed in 2070. Concurrently, carbon capture and sequestration (CCS) technologies become mature, allowing new coal and bioenergy power plants to be commissioned. Coal infrastructures with CCS produce up to 12 EJ/year in 2100. End-of-life capacities mostly consist of conventional coal, oil, and gas in the first half of the century. These are partially replaced by more efficient technologies (e.g., pulverized coal and gas–oil combined cycle), allowing increased electricity generation, while the total installed capacity remains constant before 2030. After 2040, an increasing number of wind turbines enter the end-of-life phase, while the massive installation of solar PV from 2040–2050 translates into an extensive retirement phase during the 2080–2100 period. These solar PV capacities are replaced in order to maintain production, yielding a second surge of solar panel installation. Results for each world region are in the Supplementary Material (Table S2).

3.2. Raw Material Footprint of Electricity-Generating Technologies

Constructing, operating, and decommissioning power plants requires different kinds and amounts of energy and materials, not only due to "direct" activities at the plant site, but also during upstream and downstream “indirect” activities. The total amounts of metallic and nonmetallic mineral resources and fossil fuels involved in the construction, operation, and decommissioning of EG technologies are calculated following the combination of the TIAM-FR model with the ecoinvent LCI database. In this study, metallic mineral resources represent the metal content in ore, with the remaining ore being considered as nonmetallic mineral resources. Material usage results are shown in Figure 2 for both scenarios. Total use of metallic mineral resources (Figure 2a(iv)) increases in both the baseline and 2 °C scenarios due to the increase in electricity generation. Before 2030, this is mostly driven by bioenergy, fossil fuel, and hydropower plants. In the baseline scenario, the total use of metals is shared equally between the construction and operation phases (40-55 Tg/year [teragrams per year] in 2050). In the 2 °C scenario, the use of metallic mineral resources decreases during operations to half of the 2010 level, while becoming much larger in the power plant construction phase after 2050 (up to 12 times that of the operation phase in 2090). In the second half of the century, the use of metals increases sharply due to the development of geothermal power. Although geothermal electricity production is lower than solar PV, its large requirements of reinforcing steel generate a significant material usage. At the end of the horizon, use of metals for decommissioning are 3.7 times greater in the 2 °C scenario than in the baseline, mostly due to end-of-life geothermal capacities. Demand for metallic mineral resources increases dramatically when new capacities are needed. Apart from economic growth, the 2 °C climate target sets additional pressure on mineral resource supplies. This pressure could vary depending on the evolution of recycling. However, we did not address the availability of recyclable end-of-life products in the technosphere.

Figure 2b shows the usage of nonmetallic mineral resources. Most of these resources are used during the construction of hydropower facilities, which involve massive earthworks and large quantities of concrete. However, there are considerable uncertainties and variations in the material footprint of hydropower technologies [30] depending on their design, location, and how material usage is accounted for. Significant nonmetallic resources—about 988 Tg/year in 2050 in the baseline scenario and 439 Tg/year in 2050 in the 2 °C scenario—are used by coal and bioenergy power plants due to resource extraction for operations. The use of nonmetallic mineral resources peaks in 2050 in the baseline scenario, and in 2060 in the 2 °C scenario. The decommissioning of coal, nuclear, and wind power plants uses similar amounts of nonmetallic resources in both the baseline and 2 °C scenarios until 2040. In the 2 °C scenario, cumulative nonmetallic mineral resource usage is of 121,971 Tg in 2050 and 264,370 Tg in 2100, compared to 105,116 Tg and 203,172 Tg in the baseline scenario.

Consumption of fossil fuels is mostly due to EG technology operations. The decline of coal in the 2 °C scenario is responsible for decreasing fossil fuel consumption until 2060, when mature CCS technologies enable the operation of new bioenergy and coal power plants without generating additional GHG emissions. In the 2 °C scenario in 2100, fossil fuels for decommissioning activities are five times greater than in the baseline scenario (Figure 2c(iii)). However, these fossil fuels only represent 2% of the total fossil fuel consumption.

Summing up all resources and phases (Figure 2d(iv)), we found that the 2 °C target generates 47% less material consumption in 2050 than in the baseline scenario, decreasing to 67% in 2100. However, accounting only for mineral resources (excluding fossil fuels), the 2 °C climate target generates a cumulative total use that is 16% higher over the 2010–2050 period and 31% higher over the 2010–2100 period compared to the baseline scenario. Regarding the metals only, the cumulative total use is 20% higher over the 2010–2050 period and 46% higher over the 2010–2100 period. Thus, the 2 °C target implies a transition in the resource required by EG technologies from fossil fuels to mineral resources.

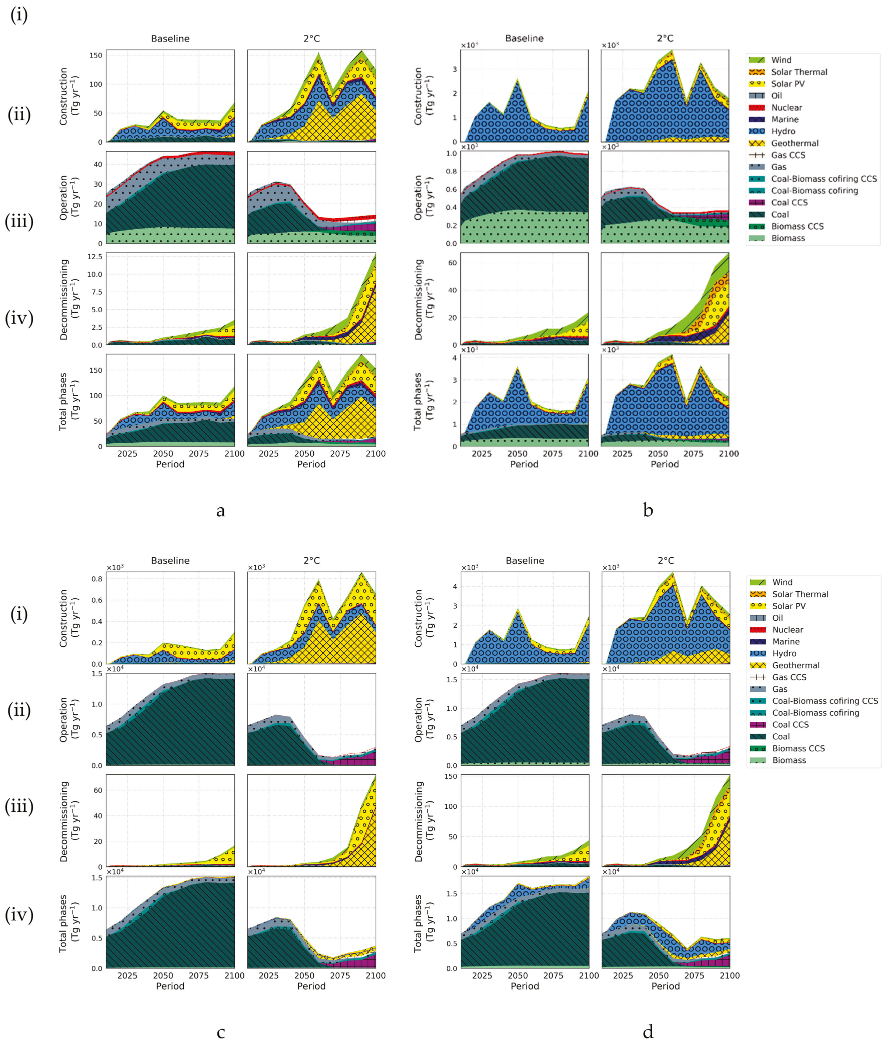

Figure 2. Use of fossil fuels, metallic and nonmetallic mineral resources in electricity-generating technologies during their construction (**i**), operation (**ii**), and decommissioning (**iii**) phases, as well as the total amount (**iv**) in the baseline and 2 °C scenarios (in Tg/yr, or teragrams per year). (**a**) Metallic materials; (**b**) Nonmetallic materials; (**c**) Fossil fuels; (**d**) Total. Full data can be found in Supplementary Material (Table S3).

3.3. Most-Impacted Substances

Figure 3a,b show the five highest increases for each decade in the use of each group of substances relative to the 2020 decade (2016–2024), in the baseline and 2 °C scenarios, respectively. Figure 3c,d shows the relative increase in substance usage between two subsequent decades. Figure 3e shows the five highest ratios between the 2 °C and baseline scenarios in each decade. Values have no units since they are expressed in relative amounts (1 ≡ 100%). Results for the three raw fossil fuels and forty-eight metallic and nonmetallic mineral resources are provided for each region in the Supplementary Material (Table S3). In the 2030 baseline decade, construction raw materials are subject to the highest increase in usage by EG technologies relative to 2020. Sand, gypsum and anhydrite, clays, gravel, chromium, and nickel are mobilized in the construction phase of EG technologies where large amounts of steel and concrete are needed. During the 2040 decade, graphite, silver and gold are increasingly used, mostly as a result of solar PV development which requires silver and gold as conducting elements, and graphite electrodes for the fabrication of silicon wafer. Wind turbines drive sand and sulfur demand up due to the need for glass fiber and sulfuric acid. After 2045, the five highest increases in material usage relative to 2020 are sand, graphite rock, silver, gold, and rare earth elements.

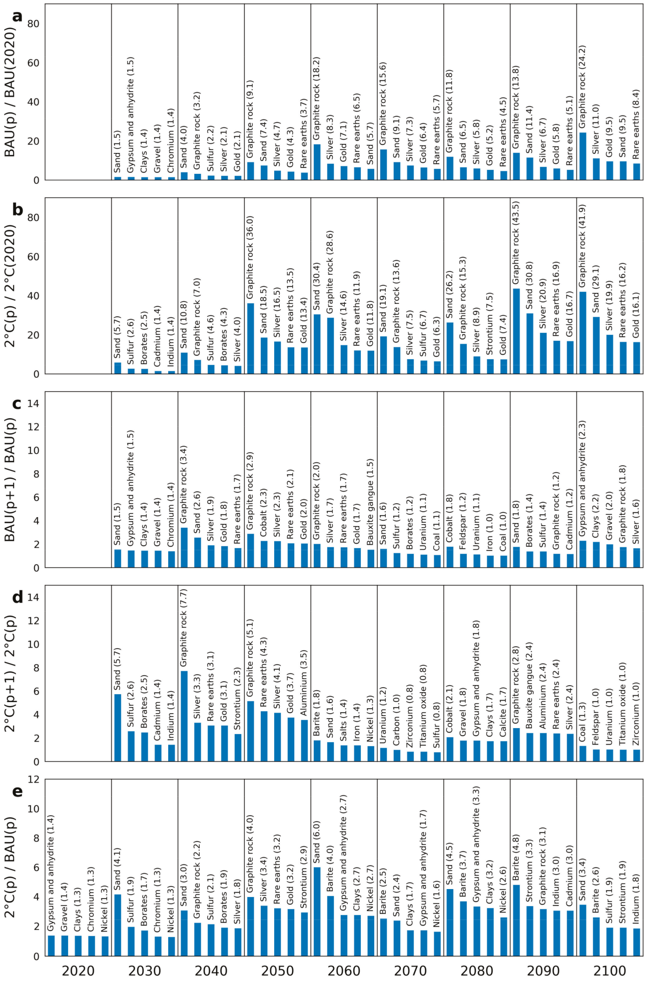

Figure 3. Relative increase (×100%) in the material use during decade p (horizontal axis) in the baseline scenario (BAU) compared to decade 2020 (**a**); in the 2°C scenario compared to decade 2020 (**b**); in the baseline scenario compared to decade (p-1) (**c**); in the 2°C scenario compared to decade (p-1) (**d**); and material use ratio between the 2°C and baseline scenarios (**e**). Trace elements, for which total usage is less than one metric ton, are not reported. Full data are in Supplementary Material (Table S3).

In the 2 °C scenario, borates (chemical agent), cadmium, and indium are the top five most increasingly used materials in the 2030 decade relative to 2020. This results significantly from the development of CdTe (cadmium telluride) and CIGS (copper indium gallium selenide) solar PV thin films. After 2040, the use of graphite, sand, silver, rare earth elements, and gold is multiplied by up to four times relative to the baseline scenario. Although marine and solar thermal electricity productions remain moderate, their relatively large material footprints generate a significant material usage in the 2060 decade. Sand (glass for concentrating solar power systems (CSP) and glass fiber for wind turbines) is one of the most increasingly mobilized raw materials.

It is important to note that a high usage increase for raw materials used in small quantities relative to their resource potential is not necessarily a subject of concern. The results for each substance should be interpreted in the context of its share of the global market and supply risk. Substances that are used in small quantities are generally those with the highest uncertainty (substances for which annual usage is less than one ton are not reported).

Looking at the relative growth between two subsequent decades in the baseline and 2 °C scenarios (Figure 3c,d), we observed that the highest increase in usage is during the 2040 decades for both scenarios. The baseline requirements of graphite, sand, silver, gold, and rare earth elements are multiplied by 1.7 to 3.4 in about 10 years. In the 2 °C scenario, graphite use soars while strontium takes over sand in the highest period-to-period increase in usage. Strontium appears in the life-cycle inventories of solar PV and geothermal technologies, for the production of zinc and thermal insulation materials. In the 2050 decade, baseline use of cobalt is 2.3 times higher than their 2040 consumption. In the 2 °C scenario, aluminum requirements increase 3.5 times in one decade. In 2060, material usage growth is more moderate as newly built low-carbon capacities enable to cut large GHG emissions. Geothermal facilities continue to develop in the 2 °C scenario. This increases the requirements of barite, iron, and nickel, used in geothermal structure and drillings. During the 2070 decade, material requirements decrease relatively to 2060 in the 2 °C scenario, with the exception of a 20% increase in demand for uranium for nuclear power plants. After 2075, raw materials are mobilized to replace end-of-life power plants, while CCS fossil-fueled technologies develop (causing an increase of 30% in coal use during the last decade).

Copper does not feature among the five highest increases in this study. However, it has become a resource of concern since it is widely used in electric appliances. Its reserves were identified as insufficiently increasing to cover future requirements due to low-carbon technologies and global electrification [31–33]. We detail the results for copper in the Supplementary Material (Figures S4 and S5), along with a comparison to previous studies of the direct metal use from EG technologies (Figure S6) [9,15,16,34]. We found average copper requirements of 0.69 Tg/year in the baseline scenario and 0.96 Tg/year in the 2 °C scenario, over the 2010–2050 period, which is in agreement with Deetman et al. [15]. Copper usage growth for EG technologies could be of 0.05 Tg/year in the baseline scenario and up to 0.1 Tg/year in the 2 °C scenario during the shifting period (2040–2050). For comparison, global mine production of copper grew at an average rate of 0.57 Tg/year between 2012 and 2017.

3.4. The 2 °C Target

By calculating the ratio between the 2 °C and baseline scenarios, it was possible to rank the mineral resources that were most influenced by the 2 °C temperature target. Figure 3e shows the five highest ratios for every decade. In 2020, gypsum and anhydrite, gravel, clays (for concrete), chromium, and nickel (for steel) are 30% to 40% higher than their baseline consumption. In the 2030 decade, the 2 °C constraint generates an average four-fold increase in sand usage compared to the baseline scenario. The influence of the 2 °C constraint is highest on sand in 2060 ($\times$ 6.0), but is also substantial on a number of substances like barite, graphite rock, silver, gypsum and anhydrite, rare earth elements, and others. At the end of the horizon, the 2 °C warming limit has a strong influence on material usage, which is multiplied up to five times compared to the baseline. Nonmetallic mineral resources, some of which are nonrenewable are impacted by decarbonation even more than metals. However, this assessment does not allow us to distinguish useful resources from tailings and overburden. Such a distinction in LCI databases such as ecoinvent could help better determine the value and criticality of a given substance.

4. Discussion and Path Forward

4.1. Static vs. Evolutionary LCIs

The approach presented here uses attributional LCIs that are static, which means they are not modified according to an evolving background. This generates bias on long-term scales when the background of a process significantly differs from the initial inventory [19]. However, this approach offers the triple advantage of: (1) capturing real situations with existing activities, (2) being able to compare EG technologies on a more objective basis, and (3) providing highly reproducible results without the need for the additional assumptions of a consequential analysis. Using evolving LCIs can be conceptually more valid, but it can also lead to special case scenarios that are perceived as less likely or less consensual. The difficulty of dealing with uncertainty in LCIs and integrated assessment models and prospective exercises has been previously discussed [28] but is not resolved here.

4.2. Resource Depletion and Footprint

The influence of prospective energy scenarios and climate targets on future mineral resource use is still largely unknown. Conversely, the influence of mineral resource availability on integrated assessments with climate targets has not yet been studied.

As many mineral resources are extracted and transformed by human activities faster than they re-form [4], future socioeconomic development and climate action may be constrained by mineral resource availability. The direct consequences of resource exploitation unsustainability include an increasing number of challenges for the mining sector (exploration and extraction) [35], resource depletion, and a growing number of critical raw materials for various stakeholders [36]. Eventually, supply disruptions may result in volatile commodity prices, enhanced intersectoral competition [37], "black swan" events [38], increased environmental impacts, geopolitical tensions, and climate action withdrawals when a given resource supply becomes a greater concern than its associated environmental impacts.

Concurrently, lower-grade mining ore [4,39–41] may result in the need for more exploration, extraction, processing, and waste for each unit of raw material produced. Additional GHG emissions could result from low resource availability if mining technologies run on fossil fuels. Alternatively, low-carbon mining technologies may reduce GHG emissions but have a larger mineral resource footprint, raising important questions about resource efficiency [40]. Environmental impacts based on mineral resource demand scenarios have been studied previously [18,42,43]. These studies have considered decarboning electricity generation to 2050, but have not addressed an increasing mineral resource footprint of upstream activities, which could lead to significantly different results. Accounting for reuse and recycling may in turn mitigate the mineral resource footprint. Thus, variations in efficiency and resource intensity should be accounted for considering the rebound effect [44] and, if possible, taking a cradle-to-cradle life-cycle perspective compatible with the laws of thermodynamics.

4.3. Other Energy Sectors

Aspects of nonfuel mineral resources that can potentially impact energy scenarios could represent key constraints in energy and environmental policies, especially when strong GHG mitigation actions are taken. Our results show that without significant changes in the constitution of EG technologies, several mineral resources will be needed by multiple times their current requirements, as a result of the wide development of material-intensive low-carbon technologies. However, resource requirements for EG technologies might only represent a fraction of the total resource consumption in the global economy. This is why a similar approach should be extended to cover other technologies and sectors of the energy system. It could be useful to policymakers, energy modelers, industrial ecologists, and industrials interested in the future material footprint, criticality, and environmental impacts of their products, technologies, and activities. In addition, life-cycle analysts could use such a tool as a basis for developing scenario-based consequential LCAs, making it easier to highlight errors and data gaps, as well as to determine adequate system boundaries in a life-cycle sustainability analysis (LCSA) [45]. The multiregional description of the energy system in TIAM-FR could be used to perform regional criticality analysis of various substances, possibly leading to geostrategic analysis. Global electrification of the world may modify the material footprint of the electricity generation and electric products. Based on this study, prospective criticality and supply chain assessments in relation to environmental policies could help identify the resources for which criticality or supply risk is high [46]. However, an endogenous integration of nonfuel resource cycles in TIAM-FR still has to be achieved.

4.4. Towards Simpler and More Complex Models

Resource prices, reserves, access, functions, services, geographical distribution, trade, cycles, and non-GHG environmental impacts are features that could potentially be integrated into IAMs to take into account resource constraints.

Dynamic material flow analysis, life-cycle inventories, and energy system modeling can all be used as prospective tools to analyze the evolution of the socioeconomic metabolism and its environmental impacts. Thus, there is an opportunity for a symbiotic relation in a common framework, to achieve energy and environmental impact scenarios compatible with sustainable mineral resource flows. However, a major challenge to such an achievement is the definition of socioeconomic laws for a system that is dynamic, complex, and nonlinear in practice. A promising framework to investigate the systemic connections between material cycles and human activities was proposed by Pauliuk [47], building on the socioeconomic metabolism concept [48]. In this framework, the socioeconomic metabolism could be further characterized by a thermodynamical approach, considering the anthroposhere as a dissipative structure [49]. Future models will ideally represent the complexity of the socioeconomic metabolism, minimizing the number of required assumptions.

4.5. Shared Socioeconomic (Metabolism) Pathways

Development pathways have strong implications for mineral resources, not only in climate change mitigation scenarios but also in baseline pathways as shown in this study. The interests that drive societies evolve rapidly and modify the conditions of what is socially and environmentally acceptable. Adaptation to material restrictions may also be possible through societal changes and resource management policies. The extent to which economic growth and GHG emission mitigation are priorities compared to other environmental and societal-related impacts should be further analyzed and debated. SSPs (shared socioeconomic pathways) provide a suitable framework to discuss these questions. In their current form [29], they contain substantial information on energy, climate, economy, and social aspects, but do not contain equivalent information about mineral resource stocks, flows, services, and use in the socioeconomic system. In the perspective of mineral resource integration in IAMs, we suggest that the SSP narratives could be complemented with "raw materials" storylines whereby material in-use stocks and flows would be described in more detail using qualitative and quantitative indicators. Such narratives could better address the features of a circular economy (reuse, recycling, frugal innovation, etc.) as well as the key issue of decoupling environmental impacts from economic growth.

Supplementary Materials: The following are available online at http://www.mdpi.com/2079-9276/8/1/33/s1, Figure S1: Global anthropogenic GHG emissions in the baseline and 2 °C scenarios, Figure S2: Total primary energy supply in the baseline and 2 °C scenarios, Figure S3: Total final consumption in the baseline and 2 °C scenarios, Figure S4: Copper use in three life phases in the baseline and 2 °C scenarios, by technology, Figure S5: Cumulative copper use in the three phases and the total use in the baseline and 2 °C scenarios, Figure S6: Prospective copper use by global electricity generating technologies according to different studies, Table S1: TIAM elec. outputs, Table S2: TIAM-FR Regions, Table S3: Material use.

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Decreasing Metal Ore Grades—Is the Fear of Resource Depletion Justified?

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Abstract: Metals are an essential part of modern living. Ensuring the future supply of metals is a key issue in politics, science, and economics because the available amount of mineral resources is limited. To measure the depletion of mineral resources, several indicators are used. Some of them are based on the ore grade, which has been decreasing over time and is thus taken as a sign of resource exhaustion. However, does this assumption hold true? This paper shows that the development of ore grades is mainly the result of the increasing demand and the outstanding technological improvements that made mining of low grade ores profitable. The usage of ore grades as an indicator may, therefore, lead to erroneous conclusions about the safeguard objects. These are not the metals themselves, but the environment that is impacted by their extraction.

Keywords: resource depletion; ore grade; metals; copper; influencing factors; indicators

1. Introduction

Mineral resources, especially metals, are essential for the development of our society. As the available amount of these resources on Earth is limited, their depletion is a key issue in politics, economics, and science [1–3]. To measure resource depletion, several indicators have been developed [4]. Some of these indicators, such as those used by the common impact assessment methods ReCiPe [5], IMPACT 2002, and the EI99 [6,7], are based on the metal content of the ores (ore grade). It is assumed that an ongoing extraction leads to a decline in the quality of the deposits still available, such as a decrease in their ore grade. It has been shown in numerous studies that the ore grades of mined deposits have been falling over time [8–11]. What has to be questioned, however, is why the ore grades have been decreasing. Is this a geological phenomenon and hence a sign for resource depletion? Or is it rather a complex interplay of geological, economic, technological, and social factors? This question plays a central role, as already discussed by Northey, Mudd, and Werner [12]. It is the starting point for further considerations on the appropriate indicators to evaluate resource scarcity and the actual safeguard objects, and thus leading to corresponding strategies for action. Therefore, this paper examines the influencing factors on the development of ore grades, using the example of copper. Copper has been one of the first metals to be mined and still plays an essential role for our modern society. Its valuable properties—for example, its high conductivity—make it a useful material for a wide range of applications. Nevertheless, other metals are also faced with declining ore grades and, depending on several factors such as demand and extraction, the arguments might hold true for them, although further research is needed to make valid statements.

2. The Development of Ore Grades

There are some basic theoretical concepts describing the quality of the available amount of minerals in our earth. The first investigations on tonnage and grade of metal deposits go back to

Lasky [13]. Lasky's Law states that while the cumulative quantity of ore is increasing logarithmically, the metal content of the total available quantity decreases linearly. This model can be applied to individual deposits as well as to a number of deposits. The density function of the total resource base was examined by Ahrens [14,15] and Skinner [16]. Ahrens assumes a log-Gaussian distribution. Skinner, in contrast, states that the density function follows a bimodal distribution. Even if the bimodal distribution seems plausible, it has not yet been proven, because we do not know the actual density function of the entire resource base on Earth.

Investigations on the development of the actual copper contents of mined ores are also available. A well-known study is provided by Mudd [8]. In his report, "The Sustainability of Mining in Australia", the author highlights the development of Australian raw material extraction and its implications for the environment. He considers not only copper but also other important mineral raw materials, such as coal, titanium, gold, nickel, and diamonds. The main data sources for his work are reports from mining companies and publications from authorities such as Geoscience Australia. As many reporting systems—for example, the Australasian Code for Reporting of Exploration Results, Mineral Resources, and Ore Reserves (JORC Code)—were not introduced until the 20th century, older data are taken from individual publications on mines or regions and are not complete for all years and raw materials. Nevertheless, the resulting error is negligible for a general trend statement over the long term. With regard to the ore grade, there is a general downward trend for all commodities [8]. Data on copper ore grades are also available for the United States. The United States Geological Survey (USGS) publishes annual reports, such as the Minerals Yearbook (USGS var.), which include production statistics for more than 90 materials. The compiled data are based on industry surveys conducted and statistically evaluated by the USGS. Figure 1 shows the development of the metal content of copper ores for Australia and the United States.

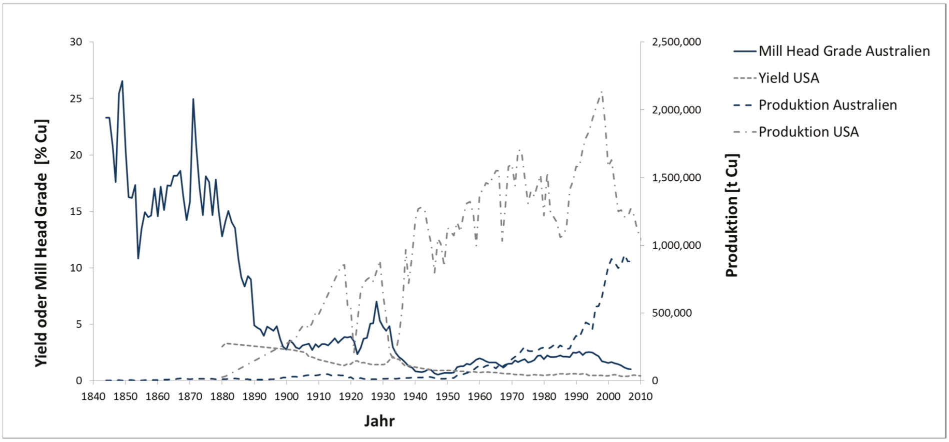

Figure 1. Copper ore grades and production in Australia (1844–2007) and the United States (1880–2010). Data for Australia are taken from the work of [8]; data for the United States 1924–2010 are taken from the work of [17], and previous years from the work of [18].

What is interesting about Figure 1 is the sudden drop in the metal content of Australian ores around 1885 from a level of approximately 15% to 5%, despite almost constant production. Taking a look at the data basis, it becomes apparent that the data availability is poor in this period of time. Around the years 1882 to 1889, only about 30% of copper production in Australia is covered, and in some cases, much less. In general, data availability between 1850 and 1890 is less than 50% of production with few exceptions, while in the other periods, it is usually in the upper quarter [8]. In addition, production volumes in Australia are relatively small and spread over a few mines, so individual mines have a relatively large influence. One of the mines, Mt Morgan, was partially destroyed by fire in 1927 and was not fully productive again until the 1930s. Mt Morgan had a low ore grade (0.5–1%) compared with the other mines, but a relatively high production share (approximately 20%), which led to a short-term increase in the average ore grade for these years [8]. Another increase in the ore grade was caused by Olympic Dam, which was discovered at the end of the 1970s, and the associated IOCG (iron oxide copper gold) deposit type was introduced [19]. Such events are more or less random, but have a great influence on the ore contents shown. Also, the base of measurement of ore grades might be different for earlier data. As exploration and sorting was done by eye or hand, respectively, a process of pre-concentration by these activities took place.

Compared with Australian copper ore grades, the metal contents in the United States are lower and their development is smoother. Crowson [11] also confirms this in comparison with the global average for the last decades. One reason is the deposit type available in each region. There are mainly porphyry deposits in the United States, which (as will be discussed later) have a low ore grade on average [11,20]. In Australia, deposits of the IOCG type currently have the largest share of resources (approximately 60% in 2010 and 2013). This type of deposit has an on average higher ore content than porphyry deposits [20–22]. Another reason is that the data represent different values. The USGS reports the yield, while for Australia, the mill head grade is given. The yield is the obtained amount of metal per amount of ore extracted. Data from the 19th century to the first half of the 20th century often state this value. Compared with the mill head grade, which indicates the metal content of the ore processed in the mill, the yield also includes the technical efficiency of the processes and is thus slightly lower than the corresponding mill head grade. Yield and mill head grade have become more and more similar with the increase in efficiency over the years [23,24]. This leads to a flattened curve in the case of the United States. The term ore grade is often used for the head grade and the yield, which makes it difficult to clearly separate the different figures. Usually, the ore grade refers to the metal content of the available reserves and/or resources. The reserves are the part of the raw materials that is known and can be mined economically under current conditions. Resources, on the other hand, describe the amount of ore (within a deposit) that cannot be economically extracted under current conditions or is associated with a higher degree of uncertainty, for example, with regard to its shape, quantity, and quality. In addition, there is the geopotential, which contains the existing, but not yet known potential of further raw material deposits. The limits of reserves and resources are thus dynamic and change, for example, with the current price [25]. However, it is important to be aware of which values are stated in order to make valid statements, because the discussed difficulties may lead to interpretations that are not compatible with the original data basis. There are several influencing factors that determine the grade of the ore mined, such as technology. Over time, an increasing efficiency, for example, made the mining of low grade ores economically feasible. This is reflected in the data shown in Figure 1, which refers to ores that actually were or are mined, not to the still available known or even unknown deposits. The influence of these factors often leads to a decrease in ore grades of mined deposits, but does not reflect depletion.

3. Influencing Factors on the Ore Grade

The influencing factors on the ore grades of mined deposits will be discussed in the following section.

3.1. Deposit Types and Demand

We extract our raw materials from the Earth's crust, which accounts for about half a percent of the Earth's total mass and consists mainly of oxygen and silicon [26–28]. Metals are contained in very small quantities in the Earth's crust. For example, the average proportion (Clarke value) of copper is about 28 ppm, while that of gold is only 1.5 ng/g [29]. The extraction of this average concentration is (at the moment) economically impossible. However, local enrichments of these elements took place as a result of different geological processes, and thus offer a suitable starting point for their extraction.

The average enrichment factor required for extraction depends on the type of raw material and the currently available technology. To extract aluminum profitably, for example, the enrichment factor has to be approximately four, which leads to an average ore content of 30%. In contrast, chromium, which is also mined with an ore grade of 20% to 30%, must be enriched approximately 3000 times because of the low average crustal concentration. For copper and nickel, the necessary enrichment factor is about 75, while for gold, it is 250 [30,31]. There is also a difference between the deposit types of one metal. Copper offers an illustrative example. Most (about 60%) of the currently known global resources are contained in so-called porphyry deposits, followed by sediment-hosted deposits (about 15%) and IOCG deposits (about 10%), among others [20]. Each of these deposit types is characterized, among other things, by its mass of ore contained and its medium ore grade. Currently mined or under development IOCG deposits have an average of 6 million tons of valuable metal at an average ore grade of approximately 0.9% Cu, sediment-hosted deposits contain 4.5 million tons at about 1.9%, and porphyry deposits contain about 3 million tons at about 0.5%. Massive sulfides (MS), which make up less than 2% of the global resources, have only about 0.3 million tons of copper at an ore grade of about 1.4% Cu (but they have remarkable amounts of other metals like zinc) [20]. Figure 2 shows the currently known resources (deposits) by type, ore content, and ore grade. What can be clearly seen is that most copper is contained in large deposits, which, however, are characterized by a low metal content of the ore. The low ore grade of large deposits reflects not only geology, but also economics. In order to state their resources, companies have to define a so-called cut-off grade, which gives the lower limit of ore grades that distinguishes waste from ore resources. This lower limit is influenced by production costs, which might be lower for bigger operations as a result of economies of scale resulting in a lower stated ore grade [12]. Another point that is important to note here is that in the future, new deposits or part of deposits as well as totally new ore types might still be discovered.

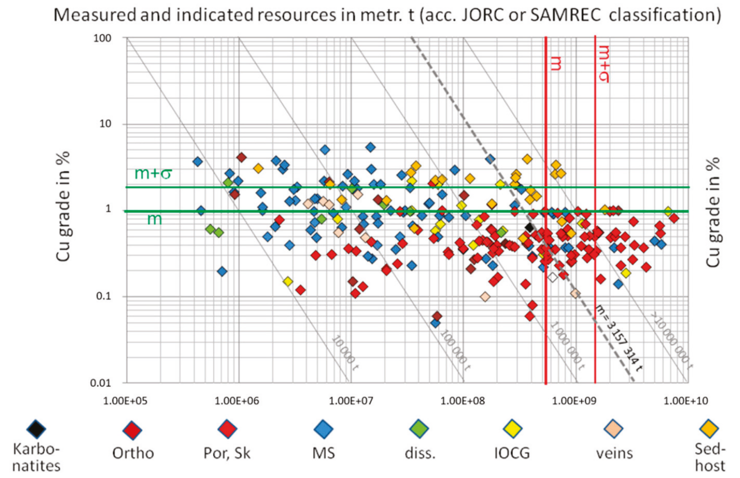

Figure 2. Resources (measured and indicated in conformity with the Australasian Code for Reporting of Exploration Results, Mineral Resources, and Ore Reserves (JORC) or South African Mineral Codes (SAMREC)) and ore grades of copper mines and projects classified by deposit types [20]. MS—massive sulfides; Ortho—orthomagmatic; IOCG—iron oxide copper gold; diss—disseminated hydrothermal; Por—porphyry; Sk—skarn; Sed-host—sediment hosted.

Assuming a rising copper demand in the long term, low-grade deposits offer a valuable source to cover this high demand and, therefore, their extraction is unavoidable [23]. If the ore contents are compared with the production over the past decades, this is made clear once again (see Figure 1). The growing population, its development, and the associated increasing use of technologies lead to a steady increase in the annual demand for raw materials. Initially mined regionally and for the company's own needs, today, enormous quantities are extracted globally and increasingly large deposits with lower ore contents are used. However, this does not mean that there are no deposits with high ore grades left. An example is the Timok Project [32]. Some of the resources have a copper content of 17% to 19% at a level of about 2.8 million tons of copper [33]. This corresponds to approximately the annual consumption of the United States around the turn of the millennium, while currently, consumption is even lower.

Moreover, ores with a high metal content are often part of a larger deposit. High-grade ores are produced by secondary enrichment, that is, they represent the oxidic zone of a deposit. Whereas in the past, only this part was mined, today, the entire deposit is used, which reduces the average ore grade of the deposit and thus of the mined ore [34]. However, as more of the available resource is extracted, this might be seen as a more efficient use of the deposit in general, which, for example, makes an important contribution to the economy of the communities hosting the mining operations.

At the beginning of copper mining in Australia, the ore content of the secondary enrichment zones was still so high that the ores were shipped to Wales for metallurgical processing, where the necessary know-how was available. Only in the course of the years, when the metal contents of the ore sank, were metal smelters established locally [35]. Thus, if only a few tons of copper were needed today or if only the high grade parts were mined, it would certainly be possible to obtain mineral resources from sources with a higher metal content than the average ore used, and there might be periods of lower demand in the future. It has to be kept in mind that the decision for developing a deposit into a mine is not entirely based on size or ore grade; there are several other factors like economics, accessibility, and political stability that come into play. Porphyry deposits, for example, are not only huge, but also near to the surface, and thus easy to access and mine by mass mining methods.

3.2. Exploration

The fact that low grade deposits are mined today is also the result of growing knowledge of their formation, occurrence, and the corresponding technologies. Whereas exploration used to be done with the naked eye at the beginning of mineral extraction, more sophisticated methods were gradually added. In addition, the economic pressure on mine operators increased, which made more precise exploration necessary, as this was the only way to make a reliable statement about the yield of a deposit and to attract investors. The first institutions dealing with mining from a scientific point of view were founded in the middle of the 18th century. About 100 years later, the USGS was established, and from this time onwards, geological explorations were carried out in all industrial countries. At the end of the 19th century, technical innovations such as diamond drills enabled deeper, more accurate, and cheaper explorations. In the 20th century, further technical developments were added, such as aerial survey and satellite imagery. From the 1980s onwards, geographic information systems (GIS) and computer models were used, for example (see Figure 3). Besides technical innovations, an increasing understanding of the structure of the earth, such as the discovery of plate tectonics in the 1960s, led to a more targeted search. This resulted in more precise models of individual deposits, and thus also to discoveries of new parts of already mined deposits. Altogether, these developments have enabled the resource base to be constantly expanded [35–37]. If we look at the reserve figures for copper over the last 50 years, we can also perceive an increase. This shows that the reduction in reserves can be compensated by exploration work and the development of extraction technologies (which will be discussed below). In times of high demand and associated high metal prices resulting from a supply deficit, exploration also increases [38–40], and there is no end in sight. In a report from the German Academy of Sciences, it is pointed out that there is no institution in the world with the capability of evaluating all the mineral deposits on Earth [41] (p.26). Therefore, there are still some white spots on the world map, contrary to the assumption that everything has already been explored [42] (p. 123).

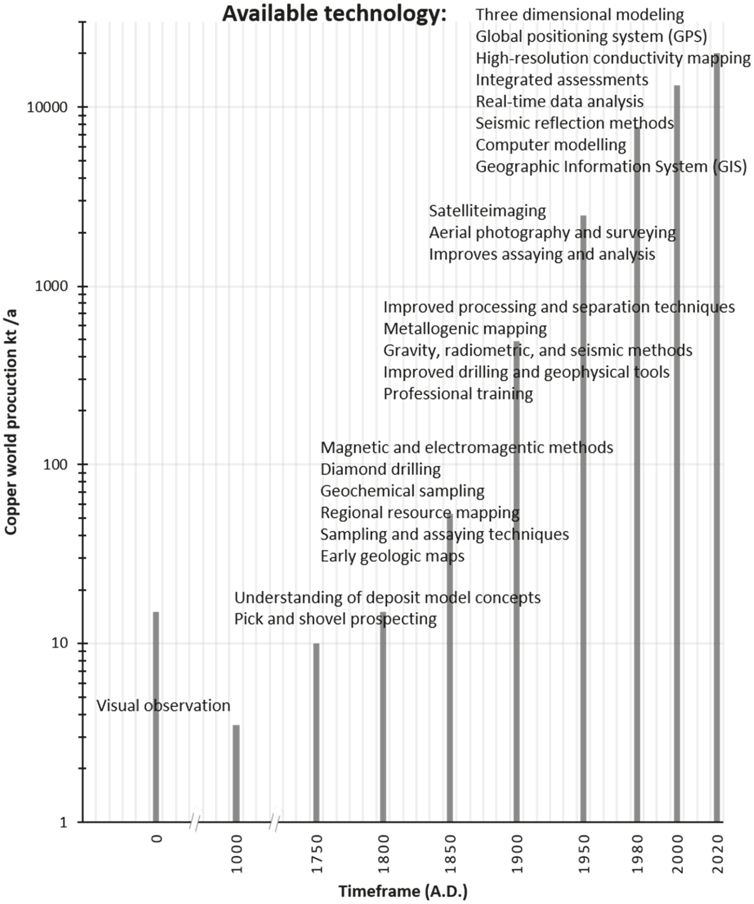

Figure 3. Development of exploration technology and mineral production [36,37].

3.3. Mine Size and Structural Changes

The choice of large deposits is not only the result of the high demand; economic reasons play also a central role. Despite the progress mentioned above, exploration and development of a deposit involves high financial costs. One way companies seek to achieve economies of scale is by spreading their fixed costs over a larger production volume [43]. This can be illustrated by the development of the capacities of mines, which is shown in Figure 4.

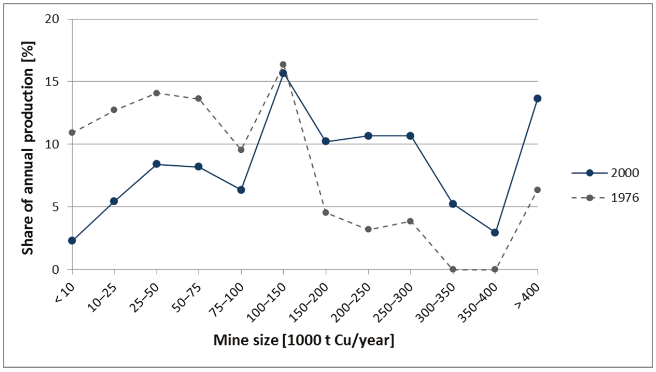

Figure 4. Share of annual production according to mine size for the years 1976 and 2000 [43].

While the decision to develop a mine before the 1980s was based on the expected copper price, in recent decades, there has been a trend towards developing only the world's largest known deposits [44]. Most of these large deposits are porphyry. In the United States, the trend towards these deposits dates back to the beginning of the 20th century. While in 1907, the proportion of porphyry deposits in the United States was still about 10% of the mined ore, in 1914, it was already about 50% and in the mid-1930s, about 70% [23]. Worldwide, porphyry deposits accounted for 34% of global mine production in 1975 and 62% in 1998, followed by a slight decline to 55% in 2009 [11]. This shows that the increasing extraction of porphyry deposits has significantly contributed to the reduction of the average ore grade. The period from the 1920s is also known as "The Porphyry Era" [23]. This era is marked by a regional shift in mine production, as shown in Figure 5. In 2008, almost half of the extracted ore came from Latin America, which has large porphyry deposits for geological reasons. For comparison, in 1931, its share was just under 20% [11,45]. The development towards large porphyry deposits is reflected not only in the size of the individual mines and their geographical location, but also in the structure of the mine operators. In the 1920s, three companies, Anaconda Copper Mining Company, Kennecott Copper Corporation, and Phelps Dodge Corporation, produced approximately 35% of the total American copper production, 10 years later, they produced as much as 74% [18].

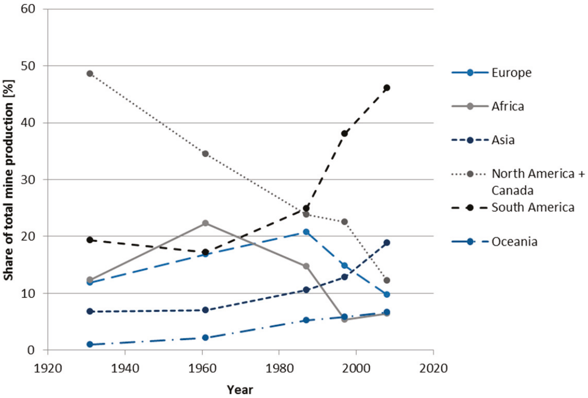

Figure 5. Regional share of annual production [11,17].

3.4. Technological Developments

Porphyry deposits were already known in the 19th century, but it was not feasible to mine them profitably; they were regarded as worthless. Only with the development of corresponding technologies did it become possible to extract low-grade deposits [18,23]. The trend towards porphyry deposits is also linked to the trend towards open-pit mining. This leads to a further decrease in the ore content, as large scale open pit mining methods allow profitable extraction of such ores because of lower mining costs. A comparison of the ores mined above and below ground reveals a clear difference in their ore grade. This is exemplified by the data for the United States from Leong et al. [18] for the years 1917 to 1936 and based on Weber [23] for the year 2013. In the first period, the difference averaged 1.3 percentage points; in 2013, it was around 0.5 percentage points (with a ratio of surface to underground mining operations of around two-thirds to one-third). Open-pit mining is a highly productive mining technique, as many of the large deposits are close to the surface. The associated method is known as the Jackling method and is one of the most important innovations from the beginning of the 20th century. Daniel C. Jackling, who developed the method, is also known as the Henry Ford of copper mining. He successfully applied the mass production methods already used in other industries to copper mining. In Bingham Canyon, for example, all underground mines were quickly converted into open-pit mines and the ore was mined with machines suitable for mass production [46–48]. At that time, it was difficult for small underground mines to keep up. In addition, there were numerous technological advances, which were necessary, among other things, to realize mass production in hard rock mining. This progress has been made in both open-pit and underground mining. In open-pit mining, large shovel excavators were used from around the beginning of the 20th century; this technology had been adopted from iron ore mining and led to a further decrease in ore grades, because larger equipment is less selective and the ore is diluted by waste or low grade material. A new invention was the block caving process for the underground extraction of copper ores with a low metal content [18,23]. This method is usable for big ore bodies with favorable rock conditions for natural breakage as it uses the internal rock stresses to fracture the rock. Therefore, an ore block is undercut by blasting; gravity causes the fractures to spread out and forces the ore block to collapse, following that the ore can easily be extracted [49]. Figure 6 shows the development of mining methods from 1880 to 1936. Today, 80% to 95% of copper ore is extracted by open-pit mining [50] (p. 197).

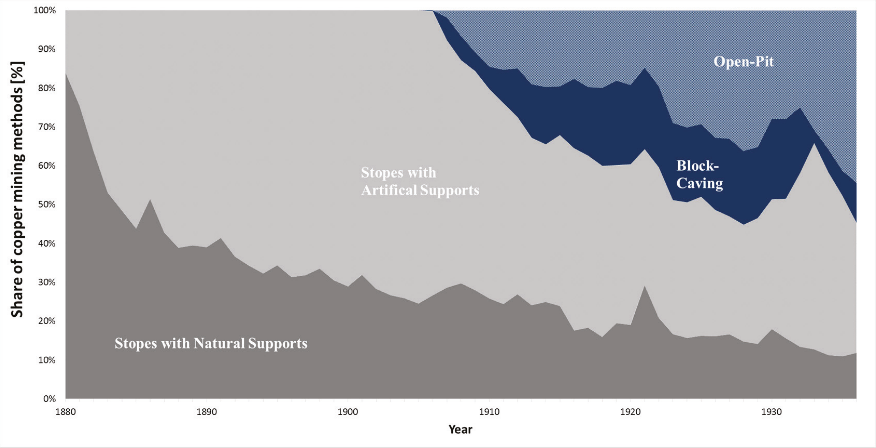

Figure 6. Shares of mining methods for the years 1880 to 1936 [18].

Even before this time, however, progress had already been made. While copper was still largely mined by hand until the 1880s, more mature and increasingly mechanized technologies were gradually used. Initially, workers used shovels to expose the ore and crushed it by hand before loading it onto carriages pulled by animals. The mechanization of these steps took place gradually. This was compounded by the increasing use of electricity instead of steam from the year 1900 (see Figure 7) [18,23,51].

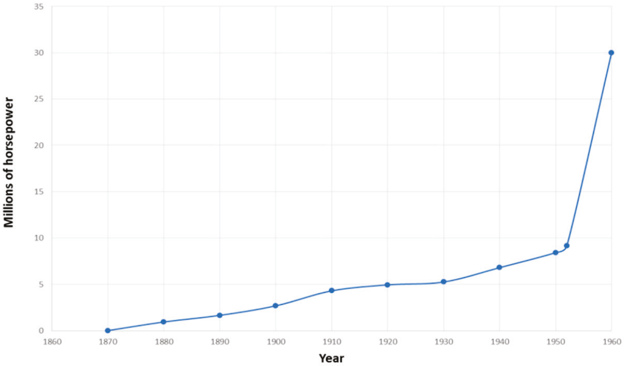

Figure 7. Mechanical power use in US metal mines [51].

Besides mechanization, the increase in the efficiency of mining, concentration, and refining technologies took place. At the end of the 18th century, drills were gradually optimized and operated using compressed air and explosives were used instead of black powder. This improvement had a particular impact on underground mining and increased the efficiency of the workers employed so that their labor could be used for other purposes. The transport systems were also upgraded and the first ventilation systems were installed. In open-pit mining at the beginning of the 20th century, the more efficient loading devices paid off. Instead of steam-powered ones, electric shovels were used, which were mounted onto a crawler instead of a truck. This allowed an increase of up to 200% of the loaded quantity. In general, larger and/or electrically operated devices were used for transport [18,48]. The mentioned developments could be described as a shift in activities from the selective mining of rich ores to the large-scale mining of low-grade ores [23].

Furthermore, technical improvements and innovations in ore comminution and concentration contributed to the success of low grade ores. The increase in efficiency achieved by technical progress is excellently illustrated by an example from Corry and Kiessling [23]. At the beginning of the 20th century, the yield after grinding was around 60% to 75% and increased to 90% by the mid-1930s. This means that the yield from an ore with 1% copper in 1935 (90% efficiency) was the same as from a 1.5% ore in 1900 (60% efficiency). This also led to the fact that old processing residues were now partly regarded as ore and processed again. Another outstanding invention was the flotation process. So gradually, the mining of more complex and chemically more diverse ores became possible [36]. In addition to purely technological advances, more and more was invested into the training of workers, which also had a positive influence on the yield [18,23].

Recent technological developments include the hydrometallurgical process, in which the metal is dissolved from the rock using chemicals before being further processed by solvent extraction/electrowinning (SX/EW). This method is used for copper oxides, which could not previously be mined, and for sulfide ores with a very low copper content. This process was introduced in 1968 and had its breakthrough in the mid-1980s. Since then, the share of total production has increased from 30% of American production in the 1990s to about 45% in 2005 [17,36]. There are also numerous innovations and process variants, for example, in the smelting process. However, the outstanding technical improvements were introduced at the beginning of the 20th century; today's innovations (apart from the hydrometallurgical process) are often process improvements to reduce the consumption of consumables and supplies and to reduce emissions. Nevertheless, new disruptive innovations cannot be ruled out (e.g., deep sea mining).

3.5. Price and By-Products

The previously listed improvements were able to offset the increasing production costs due to lower grade ores, so that the real price of copper has been constant over time [19,48]. This clearly contradicts the assumption that there is a shortage. The price is determined by demand and supply. If there is a supply shortage, the price rises. However, the constant real price in this case confirms that demand can be met at reasonable conditions.

The current market price also has a short term influence on the mined ore. Selective mining takes place in times of low metal prices. At times of high market prices, overburden previously considered worthless becomes ore. Looking at the price of copper and the grade of ores in the United States, this effect can be seen around 1930, when the global economic crisis took place. At that time, copper prices fell relatively sharply, leading to reduced mining [45]. At the same time, however, an increase in the average mill head grade can be observed. From 1933 onwards, there was an upward trend in copper prices and the average metal content fell from 1.9% in 1934 to 1.5% in 1936 (as the published reports do not include data from Alaska, this trend is somewhat more pronounced) [52]. Figure 8 shows the relative price and head grade change compared with the previous year for the period from 1920 to 2010; a positive price change is usually associated with a negative change in the copper content of the mined ore and vice versa. Not all aspects are taken into account in the evaluation, for example, a slight time shift of the effects may result from accumulated inventories; furthermore, the price of copper is influenced by a multitude of factors.

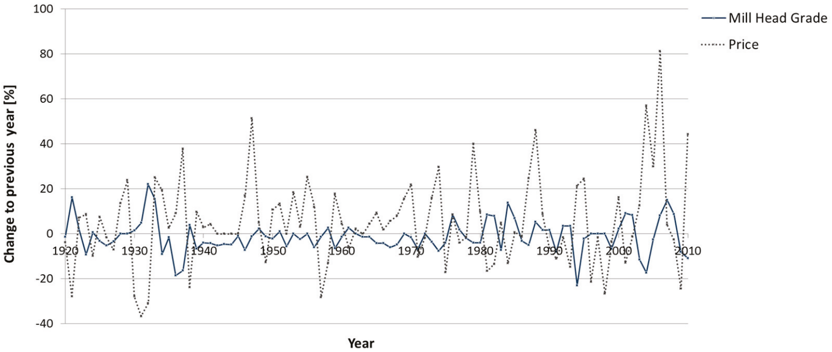

Figure 8. Relative change of copper ore grade and price for the United States from 1920 to 2010 (own calculations based on the work of [17]).

In addition to the prices for the main product, the share of by-products also represents a surplus value. Depending on the type of deposit, other different metals can be contained. Porphyry deposits usually contain copper, gold, silver, and molybdenum. Sediment bound deposits, which mainly occur in Africa, contain cobalt in addition to copper. However, there are also deposit types that have zinc and lead included as other valuable materials. Figure 9 shows the metal content of several deposits using copper equivalents. Copper equivalents give the percentage of valuable metal in a deposit, reflecting the monetary value of all metals normalized to that of copper. If the copper equivalents are compared to the copper ore grade, it can be seen that some deposit types like massive sulfides, which are often smaller, have a high added value due to the by-products they contain. On average, about 16% of the economic value of copper deposits is due to their co- and by-products [41] (p. 72).

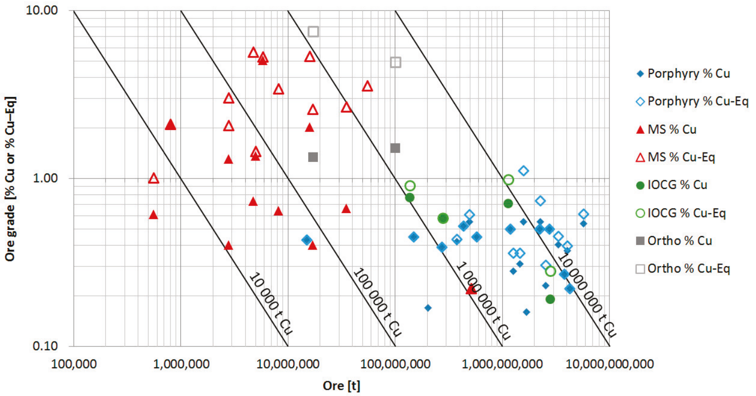

Figure 9. Resources and ore grades of copper mines expressed in Cu–Eq (own calculations based on the work of [22], Cu–Eq are calculated using the amount and price of all in a deposit included and extracted metals, efficiencies are neglected).

Figure 10 shows the development of the amount of molybdenum, gold, and silver produced in the United States as a by-product of copper production per ton of copper (over individual years). The amount of silver extracted is quite stable over the period evaluated, whereas the proportion of gold falls over the same period. In 2000, approximately 45% less gold was mined per ton of copper than in 1950. For molybdenum, the case is reversed. Molybdenum production from copper mining more than doubled (the figures also include the by-product quantity from other mass metals, but this proportion is negligible in comparison with that from copper). One reason for this is the demand for molybdenum, which had been increasing steadily since the mid-1930s and only flattened out towards the beginning of the 1980s.

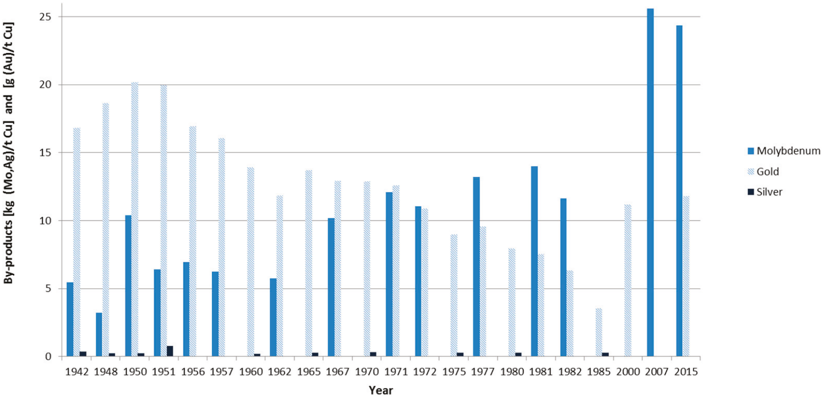

Figure 10. By-products per ton of copper production (own calculations based on the work of [17]).

On the other hand, the increasing share of porphyry deposits in the total copper production also contributes to this, as only porphyry deposits contain molybdenum as a by-product. The proportion of molybdenum, which is mainly extracted from copper as a by-product, rose from 27% in 1942 to over 56% in 2015, with the other half of annual production currently being extracted as the main product [17]. Unfortunately, no statement can be made for cobalt, as this is hardly produced in the

United States. Apart from the copper content, it can be shown that the amount of by-products obtained has increased overall and thus contributes more to the profitability of a mine.

4. Discussion

The ore contents of the mined copper deposits have been decreasing over the last decades. Mudd, for example, confirms this not only for copper, which has been used here as an example, but also for many other metals that are mined in Australia [8]. Often, this trend is used to support the view that we are running out of resources. However, as shown by this work, this conclusion cannot be drawn from the available data. Instead, we need to interpret this trend positively and see the enormous technological progress associated with it.

Regarding the decreasing ore grades, the first statement may seem appropriate, but we have to acknowledge that these figures show the ore grade of the actual mined deposits, not what is still available in our earth, and there are several other factors that have an influence on the choice of whether or not to mine a deposit. It could be shown that the exponential increase in the consumption of copper, for example, led to the mining of ever larger deposits, which often have lower ore grades. This is because of the preferred deposit types. New technologies have been developed to extract these deposits, and large shovel excavators and froth flotation, for example, have made it possible to use ores with a low concentration of metal. What was called ore at the end of the 20th century was still overburden at the beginning of the same century, because it was not possible to extract the raw material under economic conditions. The long-term constant real copper prices reinforce this statement by showing that people have found a way to serve demand (using low grade ores) at reasonable prices. Therefore, the ore content alone is not suitable for making a statement about the availability of raw materials, but rather to show the enormous progress made by the technologies used.

Nevertheless, the decreasing metal content of the ores leads to an increased expenditure of input materials, overburden, energy, emissions, and so on, which must not be ignored, as it has a considerable influence on our environment, but which was not the subject of the paper here. Further, it is precisely this increasing ecological expenditure associated with falling ore grades, as well as the increasing conflicts of use, that are restricting the availability of resources from a sustainable point of view. In our opinion, these environmental impacts should be placed more at the center of the assessment of resource extraction than a very speculative discussion about possible resource depletion based on the data discussed in this paper.

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resources

Article

Critical Natural Resources: Challenging the Current Discourse and Proposal for a Holistic Definition

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Abstract: Studies on critical natural resources have grown in number over the last decade out of concern for resource availability and its potential impacts. Nonetheless, only a handful of studies explicitly define criticality for natural resources. Through a systematic literature review, we identified four main perspectives in the descriptions of critical natural resources: (1) economic importance is overemphasized at the expense of sociocultural and ecosystem support functions of natural resources; (2) a Western perspective dominates the research discourse; (3) apart from the field of economics, the debate lacks input from social sciences; and (4), non-renewable resources are overrepresented compared to renewables. Based on the current discourse and its apparent inclinations, we propose a new definition of criticality for natural resources aligned with risk theory. We argue for the need to balance out the perspectives described above to provide decision-makers with impartial information for the sustainable management of natural resources.

Keywords: critical; criticality; definition; natural capital; natural resources; raw materials; systematic mapping

1. Introduction

Natural resources are found all around us in the natural environment. However, they are only identified as such when value is attributed to them by humans [1]. The adjective “critical” has been added to natural resources increasingly often, both in scientific publications and grey literature. This comes alongside growing awareness of global trends, such as population growth, increased consumption, and pollution. Nonetheless, most often what “critical” entails is not explained and the attributive has been used interchangeably with other adjectives, such as “strategic” or “scarce”, which causes confusion over its meaning [2]. Moreover, concepts such as “critical natural capital”, “keystone resources”, and “critical raw materials” have emerged in different scientific fields [3–5]. They all address the notion that some resources are more critical than others and that, consequently, the management of those resources requires guidance. To the extent of our knowledge, there has not been any systematic exploration of what authors mean exactly with these concepts and where their understanding is the same and where it diverges.

Criticality assessment methodologies are the main way of evaluating and communicating the criticality of natural resources. They are used as systematic screening tools to identify resources of concern. Thereby, the assessments inform and guide policy making, research and development, as well as product design [6,7]. Governmental organizations and policymakers have been actively involved in the discourse and assessments of critical natural resources, evidenced, for example, in reports by the

US Department of Energy [8] and the European Commission [9]. Classifying them as critical through these assessments leads to some natural resources being prioritized over others. The discourse has influence on decision-making since the classification provides guidance for the management of natural resources. Diverging assumptions and understandings of criticality of natural resources can thus lead to different resource management and policy outcomes. Therefore, it is important to identify the main understandings and underlying assumptions captured in the different concepts.

Following this aim, the research question guiding this work is: How have critical natural resources been defined and what aspects constitute its understanding? To answer this question, this paper maps out the discourse on the criticality of natural resources. Accordingly, we investigated common grounds and divergent interpretations of the concept. The methodology of the review is presented in the following section. In the results and discussion sections, we introduce observations from the review which are directly followed by our interpretation for each insight. Several perspectives were identified in the current literature, and based on those observations, we propose a new definition of natural resource criticality.

2. Materials and Methods

We applied systematic mapping, a type of systematic literature review [10]. It is considered a suitable methodology for a transparent and reproducible review that covers multiple research fields. Compared to regular systematic reviews, a systematic map does not attempt to answer specific research questions but rather rigorously gathers and describes available information around open-framed questions [10]. The method is suited for answering policy-relevant questions, clustering knowledge, identifying knowledge gaps, specifying further (more specific) research questions, and, as is the case for this paper, developing a greater understanding of concepts. Moreover, it aligns well with Jabareen's [11] grounded theory method to contribute to the theorisation of concepts from multidisciplinary bodies of knowledge.

A brief, step-wise overview of the process we followed to develop this systematic map goes as follows: (1) establish a review team, set the scope and research question, and develop inclusion and exclusion criteria for documents; (2) document search for evidence; (3) screen documents found; (4) code evidence and store it systematically in a database; (5) describe and visualize the findings in a report [10].

The established review team consisted of the two authors with divergent backgrounds in natural and social sciences. For step two described above, we gathered documents in May 2017 by applying a similar search string to two scientific article databases: Scopus and Web of Science. The search string was carefully designed and tested with appropriate synonyms and combinations of search terms to (1) restrict the number of nonrelated articles and (2) to find as many relevant documents for our research question as possible. The latter criterion was tested by making sure a set of previously identified articles relevant to the research question were among the gathered documents. The aim of the search string was to find publications that included the keywords "natural resources", "resources", "materials", or "natural capital" in proximity to "critical", "strategic", or "key" and close to a keyword demanding an explanation (i.e., "definition" or "classification"). The exact search strings we used can be found in Appendix A. Since the search was only conducted in English, no publications in other languages were found, which is one of the limitations of this work.

The documents identified in our search were screened and selected based on their title and abstract according to predefined inclusion and exclusion criteria. Broadly, the selection criteria aimed to include documents which contained a definition or classification of natural resources. It also needed to include a description of their criticality that was not specific to one resource but generalizable to at least a set of resources. The specific exclusion and inclusion criteria can be found in Appendix B. After reading the selected documents, a reference and bibliography search was performed, where all literature citing and cited by the selected documents was screened for inclusion. The reference search, applying the same selection criteria for title and abstract, expanded the set of documents to analyse in full text from 63 to 199 documents.

Additionally, we searched through grey literature, that is, documents published in a nonstandard way for academic practices. A number of web-based databases for grey documents exist, such as www.opengrey.eu, documents.un.org, search.un.org, and publications.europa.eu. They are, nevertheless, incomplete or not functioning properly. We initially explored those databases with search strings similar to the ones defined in Appendix A. They only provided us with a handful of relevant documents. The citation and reference search we did on our gathered scientific articles included all the relevant grey documents found as well as additional ones. They included nonpublished manuscripts, reports from governmental and other organizations, conference proceedings, statutes of public law, books and book chapters, dictionary entries, and theses. The documents were selected and analysed in the same manner as the scientific journal articles.

We performed the searches and subsequent selection of documents from May to June 2017. Ultimately, 105 full-text documents were selected for further analysis. Appendix C presents a flow diagram of the number of documents in every step of the selection procedure. Appendix D lists all articles that were finally included and reviewed.

As listed above, the final step was the analysis of the selected documents by systematically coding the evidence and producing a systematic map database of coded text fragments. We used an open-source qualitative coding and analysis program called TAMS Analyzer (4.49b5ahEC, Matthew Weinstein, Kent State University, Kent, OH, USA) [12]. We followed Clapton et al.'s [13] guidelines for coding or keywording documents. Researcher triangulation lowered subjectivity in keywording by content clustering. Both authors created their own keywords based on initial analyses of each 10 documents. We discussed and merged our coding schemes to proceed in an equivalent and structured way. Halfway through the full-text analysis, we rediscussed and adjusted the coding scheme, as well as at the end. In case of doubt or disagreement, outside experts were asked for their opinion.

This resulted in the clustering of text fragments in three main topics or codes: definitions of natural resources, classifications of natural resources, and definitions and descriptions of criticality for natural resources. The third code, criticality, was subdivided into the following six subcodes: economics, environment, physical availability of resources, politics, strategy, and technology. Furthermore, each individual document was coded with the year of publication, country of first author, journal publication, and the first author's type of institution (e.g., university, private company, governmental agency, etc.). The quality of the coding process was ensured through the collaborative nature of the research. That included frequent consultation within and outside of the coding team, as well as through the documentation of procedures and decisions [13]. Text fragments, grouped by their specific codes and potential overlaps with other codes, were then analysed to reveal patterns in the data.

3. Results and Discussion

3.1. Natural Resources and Their Classification

Before being able to explore the criticality of natural resources, it is necessary to form an understanding of the term. Broad inclusion and exclusion criteria of the search method were set to both include documents defining and categorizing natural resources as well as documents concerning their criticality. Figure 1 presents the codes concerning definitions of natural resources in the reviewed documents, gathered from 38 of the 105 reviewed documents. They could be split up into three main themes. One related definitions of natural resources to the physical environment. For example, they focused on biophysical processes of nature or the finiteness of stocks. A larger group of codes described natural resources as a dynamic concept, or even a social construct, dependent on its value in relation to human needs and wants. This view, namely, that "resources become" instead of that "resources are", was already elaborately described in an industrious volume by E. W. Zimmermann in 1951 [14]. A more recent example of this view was given by Cutter and Renwick [15], who argued that environmental cognition, "the mental process of making sense out of the environment that surrounds us", lies at the base of natural resources: "A resource does not exist without someone to use it. Resources are by their very nature human-centered. Different individuals or groups value resources differently". The largest group of codes described the intersection between these two views of natural resources, acknowledging both its provision by the natural environment and its value in relation to human activities. Andersen [1], for example, states that "natural resources exist independently of humans but are only identified as resources, and thus ascribed value, in relation to human activities".

There were 29 other codes related to defining natural resources which did not fit into the value driven and/or physical environment themes. Several of them describe the concept of natural capital, coined by ecological economists, as an addition to human capital and manufactured capital. It comprises natural resources and "the ecosystems that support and maintain the quality of land, air and water, and biodiversity" [16]. Another group of leftover codes pointed to the distinction in definitions between reserves and resources, exclusively for minerals, based on classification by the United States Geological Survey (USGS). Respectively, they represent "a mineral deposit that is currently economic (reserves) and another which may become economic in the future (resources)" [17]. The economic (and technological) feasibility indicates again, however indirectly, a human-value driven definition. The five text fragments in the middle of the diagram could be considered as the most comprehensive ones. They explain natural resources from a combined environmental and value-driven approach, while also adding an extra aspect. Le Billon [18], for example, stated that definitions of natural resources are often disputed due to contesting ideas of ownership over them. Dewulf et al. [19] (p. 5312) introduced the aspect that natural resources "may have a three-dimensional (volume) or a two-dimensional nature (surface)". Terrestrial and aquatic surfaces, according to them, are for example available for harvesting, production, or infrastructure. The other three documents in the middle of the diagram are [20–22].

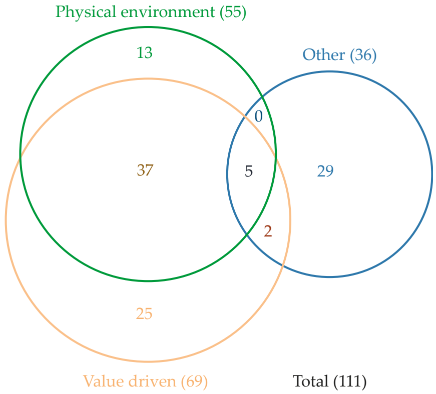

Figure 1. Venn diagram describing the amount of text fragments defining natural resources, coded into three themes. The total amount of text fragments (n = 111) were gathered from 38 of the 105 reviewed documents.

The coded text fragments make clear that both the physical environment as well as human valuation are important components of a definition of natural resources. Between all the reviewed definitions, the following one presents this duality the best in our opinion, found by Castleden [23] in a geography textbook by Daniels et al. [24]: "A substance in the physical environment that has value or usefulness to human beings and is economically feasible and socially acceptable to use". Castleden [23] thereby notes that natural resources' value can go beyond an economic one and include, for example, a role in human identity, relationships, and spirituality.

What constitutes natural resources and how they are classified is very closely related. Most often, they are classified according to their rate of regeneration: renewable and non-renewable resources. Renewable resources are defined as resources that regenerate on a human timescale (e.g., water, fish, and forests). Non-renewable resources do not regenerate over human timescales, for example, minerals. This simple subdivision is considered misleading, or even harmful by some scholars, as it leads to the belief that renewable resources will always stay available for human exploitation, regardless of their management [15]. Therefore, renewable resources can be further subdivided into unconditionally renewable resources, such as solar power, and conditionally renewable resources, such as wildlife. The unsustainable management of conditionally renewable resources can exhaust their regenerative capacity and make them non-renewable. Various terms are used to indicate these three subsequent classes of natural resources, which are presented in Table 1. From this simple table, an inconsistency in terminology is apparent between Cutter and Renwick [15] and Dewulf et al. [19]. While the former applies the term "flow resources" to conditionally renewable resources, the latter applies the same term for unconditionally renewable resources. To avoid confusion, we follow the terminology and classification of natural resources by Jowsey [25] in the rest of the paper.

Table 1. Natural resource classifications based on regenerative capacity.

Source	Non-Renewable	Renewable	
[25]	Non-renewable	Conditionally renewable	Unconditionally renewable
[19]	Exhaustible non-renewable	Exhaustible renewable	Inexhaustible renewable
[19]	Stock	Fund	Flow
[26,27]	Depletable	Critical zone	Continuous
[15]	Non-renewable/stock	Renewable/flow	Perpetual
Examples	Oil, genetic biodiversity, diamonds, metals, etc.	Fish stocks, soils, groundwater, timber, etc.	Solar, tidal, wind power, etc.

3.2. Overview of the Reviewed Publications on Criticality

An overview of the timing and location of the publications, which includes codes on the criticality of natural resources, is presented in Figure 2, as well as the subcodes/topics discussed in them. Their number amounts to 75 out of the total of 105 documents within the review. The first publication in this review dates from 1984 and focused on strategic minerals [3]. In the 1980s and 1990s, the topic was only sporadically present, and criticality was mainly related to strategy and defence. Although less dominant in the more recent literature, this continued to be a regularly discussed aspect of criticality. In the late 1990s and mid-2000s, a branch of publications focusing on critical natural capital appeared where environmental concerns were introduced into the criticality debate. From 2008 onwards, the topic started to gain more attention and grew notably up to a peak in 2015. It kept a strong presence in the literature until May 2017, when the gathering of publications for this review started. Since this new wave of interest, economic aspects of criticality have been introduced and have received most of the attention, next to technological, political, physical availability, strategic, and environmental aspects.

According to our interpretation, environmental concerns become present in the literature after the publication of the Brundtland Report [28] and the Rio Earth Summit in 1992 that both focused on sustainable development. The Kyoto Protocol was first published in 1998 [29] and the United Nations Millenium Decleration came out in 2000, which stressed the importance of sustainable development and protecting our common environment [30]. This suggests that these events, and increased global environmental awareness more generally, might have impacted the criticality discourse. Furthermore, the economic crisis of 2008 is likely linked to the increase in publications discussing the criticality concept more intensively. The European Commission report from 2010 on critical raw material [5] can also have further put the issue on the agenda, which links with the EU's action plan for the Circular Economy [31]. Since then, more weight has been placed on economic as well as technological concerns over the earlier defence and environmental concerns. Nonetheless, the topic of criticality in relation to the environment has not disappeared completely from the debate. The UN's 2030 Agenda for Sustainable Development came out in 2015 [32], which put a strong emphasis on environmental issues, further raising awareness on their importance in the global community.

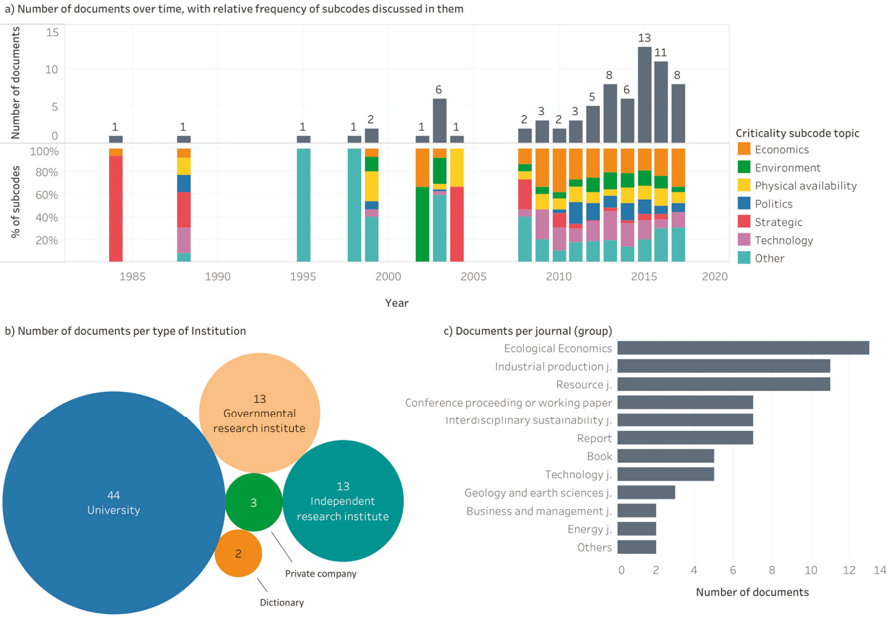

Figure 2. Overview of the publications included in the review on criticality of natural resources (n = 75): (**a**) number of publications over time, with indication on the number of subcodes per criticality aspect; (**b**) number of publications per type of organization of first author; (**c**) number of publications per type of journal (j. = journals, several grouped together from similar disciplines, see Appendix E for included journals).

Based on the location of the first author, 60% of the 75 publications were published by residents of the United Kingdom, Germany, or the United States. Additionally, publications from the Netherlands, Italy, and Canada together accounted for another 21%. The remaining publications were all produced in Western countries with the exception of two from Asia (i.e., [33,34]). Authors from the United Kingdom were the first ones to enter the debate alongside their Canadian colleagues until 2000. Dutch scientists joined after 2000 and US scholars followed in 2004. We found publications from Germany since 2009. Researchers from Italy, represented solely through the European Commission's Joint Research Centre, joined the debate in 2014. The two Asian publications in our review were both published in 2015.

These findings might indicate that natural resource criticality is a primarily Western concept. However, the search was performed in English which excludes publications in other languages. In the gathered publications, Korean, Japanese, and Russian reports were mentioned among others [35,36]. Additionally, there were no signs of standpoints in the criticality discussion from the global south. This plausible over-representation of Western perspectives could influence the understanding of criticality of natural resources since other parts of the world are not considered to the same extent.

Analysing the first author's affiliation shows that 59% of the publications were developed at universities, 17% at governmental research institutes and agencies, 17% at independent research institutes, and 4% at private companies (Figure 2). This indicates that various layers of society consider the topic to be important. The range of academic journals and other publishing media that covered studies on the criticality of natural resources was also diverse. Journals concerning resources (e.g., Resources Policy) and industrial production (e.g., Journal of Cleaner Production) accounted each for 15% of the reviewed literature. Resource journals were used as publishing media from the start, while the topic only started to appear, although frequently, in industrial production journals after 2014. Reports, often by governmental or independent research institutions, encompass 9% of the reviewed materials from 2008 onwards. Technology journals contain 7% of publications from 2011 on. Articles in the Journal of Ecological Economics represent 17% of publications which were mainly published in the 1990s and 2000s. One reason for this high percentage was the CRITINC research project about critical natural capital that ended in 2003 with a special issue on the topic in the Journal of Ecological Economics [37]. Many of the identified journals grouped above are interdisciplinary. What stood out from this review of publication platforms was that, except for a couple of economics related publications, there were few publications originating from the social sciences.

3.3. Definitions of Criticality

According to a number of scholars, the adjectives “critical”, “strategic”, and “scarce” have not been differentiated clearly from each other and, therefore, have been used interchangeably [2,38,39]. The historical conceptualisation and use of the concept “strategic” for natural resources is described by Haglund [3]. In brief, the concept was coined shortly after World War I, when shortages of certain natural resources revealed the need for industrial capacity and input to win wars. From the 1930s onwards, the concept “critical” was introduced, initially, as a separate category but later aggregated into one concept “strategic and critical materials”, which was still in use in the 1980s [3]. Currently, the terms “critical” and “strategic” are used separately where “critical” refers to threats to national economies, while “strategic” relates almost exclusively to military and defence needs [5,39,40].

Despite being a highly debated topic, many of the reviewed publications point out the fact that there is currently no universally agreed upon standard definition of criticality concerning natural resources (e.g., [2,41]). The variation in terminology is attributed to the multiple applications of the concept in diverse contexts, such as time or spatial scales [42,43]. Some authors prefer not to have a common definition so that “criticality is a relative concept and the relevant dimensions can (and should) be defined by the user according to his/her particular needs” [44] (p. 728). Some of the publications in this review did present a definition of criticality in relation to natural resources, shown in the Table 2 below.

Table 2. Verbatim definitions of the concept “critical” related to natural resources from the review in chronological order.

nr.	The Defined Concept	Definition	Source	Year of Publication
1	Strategic and critical materials	Strategic and critical materials are those materials required for essential uses in a war emergency, the procurement of which in adequate quantities, quality, and time is sufficiently uncertain for any reason to require prior provision for the supply thereof	[45]	1947
2	Strategic and critical materials	Those materials that (A) would be needed to supply the military, industrial, and essential civilian needs of the United States during a national emergency, and (B) are not found or produced in the United States in sufficient quantities to meet such need	[46]	1979
3	Critical natural capital	Vital parts of the environment that contribute to life support systems, biodiversity and other necessary functions denoted as ‘keystone species’ and ‘keystone processes’	[47]	1993
4	Critical natural capital	Ecological assets that are essential to well-being or survival	[48]	1993

Table 2. *Cont.*

nr.	The Defined Concept	Definition	Source	Year of Publication
5	Critical natural capital	Critical natural capital consists of assets, stock levels or quality levels that are: 1. Highly valued; and either 2. Essential to human health, or 3. Essential to the efficient functioning of life support systems, or 4. Irreplaceable or unsubstitutable for all practical purposes (e.g., because of antiquity, complexity, specialisation, location)	[49]	1994
6	Critical natural capital	Critical elements of the capital stock should be: 1. Essential to human health, but should also reflect the need for ecosystem health; 2. Essential to the efficient functioning of life support systems; 3. Irreplaceable or unsubstitutable for all practical purposes 4. In addition, irreversibility of environmental processes or stock changes has implications for intergenerational equity	[4] modified from [49]	1994
7	Critical natural capital	That part of the natural environment which performs important and irreplaceable functions	[21]	2003
8	Critical natural capital	That set of environmental resources which performs important environmental functions and for which no substitutes in terms of human, manufactured or other natural capital currently exist	[37] through [50]	2003
9	Critical natural capital	Natural capital which is responsible for important environmental functions and which cannot be substituted in the provision of these functions by manufactured capital	[37]	2003
10	Critical natural capital	Natural capital that is not substitutable by any other form of capital	[50]	2003
11	Critical natural capital, based on an anthropocentric perspective	The ecosystem services which are most important to our survival and well-being and cannot be substituted (focused mainly on production and information functions of natural ecosystems)	[50]	2003
12	Critical natural capital, based on an ecocentric perspective	The ecosystems which are most important to maintain environmental health/integrity (focused mainly on maintenance of regulation and habitat functions)	[50]	2003
13	Critical materials	Those [materials] for which a threat to supply from abroad could involve harm to the nation's economy	[39]	2008
14	Raw material criticality	To qualify as critical, a raw material must face high risks with regard to access to it, i.e., high supply risks or high environmental risks, and be of high economic importance. In such a case, the likelihood that impediments to access occur is relatively high and impacts for the whole EU economy would be relatively significant	[5] also referred to by [2,40]	2010
15	Raw material criticality (in the context of the general risk matrix)	In this context, raw material criticality can be interpreted as the systemic risk of damages to an economy due to disturbances in raw material supply	[51]	2012
16	Strategic or critical materials	If their supply is concentrated in one country or could be restricted by a few corporate interests, and because they are important economically or for national security	[52]	2012
17	Criticality of metals	The extent of current and future risks associated with a certain metal	[53]	2013

Table 2. *Cont.*

nr.	The Defined Concept	Definition	Source	Year of Publication
18	Criticality of metals	The quality, state or degree of being of the highest importance	[17,54]	2013, 2014
19	Criticality	The combination of the potential for supply disruption and the exposure of a system of interest to that disruption	[55]	2014
20	Criticality	The term 'criticality' describes an evaluation of the holistic importance of a resource, which can be interpreted as an assessment of the risks connected with resource production, use and end-of-life	[56] through [57]	2014
21	Criticality	A dynamic, multidimensional characteristic of materials. In other words, criticality in its meaning of "state of being critical" can refer to something as being vital, absolutely essential as well as to something that is verging on the state of emergency	[33]	2015
22	Criticality of ecosystem services	The criticality of ecosystem services depends on (i) the essential role of these services for human existence and well-being, (ii) the non-substitutability of the services with regard to their unique contribution to human well-being, and (iii) the risk of the services becoming irreversibly extinct if the natural capital that provides them is degraded beyond critical thresholds.	[58]	2015
23	Criticality of a raw material	A measure of the (economic) risk arising from its utilisation (incl. production, use, and end-of-life) for a specific consumer over a certain period	[59]	2017

The definitions found in the literature (Table 2) can be compared with the general definition of the term critical by Oxford English Dictionary Online [60] describing the terms' use and understanding in the everyday language: "Of the nature of, or constituting, a crisis: (a) Of decisive importance in relation to the issue. spec. [. . .], (b) Involving suspense or grave fear as to the issue; attended with uncertainty or risk". Many of the definitions in Table 2 describe criticality with respect to natural capital and raw materials or metals. Only two definitions, by Roelich et al. [55] and Helbig et al. [57], take a general stand or refer to resources explicitly. Further, many of the definitions seem to be derived from assessments of criticality and its specific methods, which has been noted before by Graedel and Nassar [54].

The various definitions we identified included keywords such as: risk (or threat, emergency), importance (supplemented by vital, essential), and, less commonly, unsubstitutable or irreplaceable. According to Frenzel et al. [59], many authors are not aware of the "true meaning of risk" and its fundamental links to criticality, leading to conceptual and methodological issues in research on critical natural resources. Correspondingly, de Groot et al. [50] argue that threat related to a resource should be discussed alongside the importance of a resource in the conceptualisation of critical natural resources. Concerning the importance of natural resources, de Groot et al. [50] claim that certain functions of natural resources are important "to the maintenance of the natural capital itself (especially the regulation and habitat functions)", while other functions of natural resources are "of direct benefit to human society" [50] (p. 190). Mancini et al. [44] developed a prioritization scheme of needs that resources fulfil, namely, the relative importance of their functions, adapted from the psychologist Maslow's pyramid of human needs (Figure 3). Unsubstitutable resources can be found at the base of the pyramid, described by Armstrong as "indispensable supports for the most basic functionings, and [. . .] vital supports for anyone's life" [22] (p. 15). Examples have been provided by [17], who are researchers mainly focused on minerals and metals. They [17] single out nitrogen, phosphate, and potash as the only minerals essential to life itself and, thus, unsubstitutable. They argue that all other minerals are substitutable because "it is the need or desire for the products that generates a demand for minerals, rather than demand for the mineral itself. As a result, there is always the possibility of finding an alternative material to provide the required functionality" [17] (p. 1). Next to minerals, [50] also give renewable resources, like clean air or fertile soils, as examples of unsubstitutable resources belonging in the base of the pyramid. Accordingly, they add to [17] that, although many functions of natural resources can be replaced by human inventions, it might be undesirable because it "is often technically difficult and usually imperfect, it is often socially undesirable and economically not very sensible" [50] (p. 197).

Several other aspects important to the definition of criticality for natural resources were brought up by our review. According to [50], inherent to the "importance" part of criticality is the question: important for whom? In general, most literature provides the answer that it is critical or important to (a certain part of) human society. In addition to that, some authors mention nonanthropocentric perspectives that consider parts of the natural environment as resources or even critical resources to other species than humans [23,50]. Within the dominant anthropocentric perspective, the criticality concept is guided by different interest groups such as, critical to: global human society (or humanity) [61], a region [35], a country [62], a corporation [63], an economic or industrial sector [64], or a specific product or technology [65]. This is one of the reasons why definitions and criticality assessments are considered context dependent by many authors, as mentioned earlier.

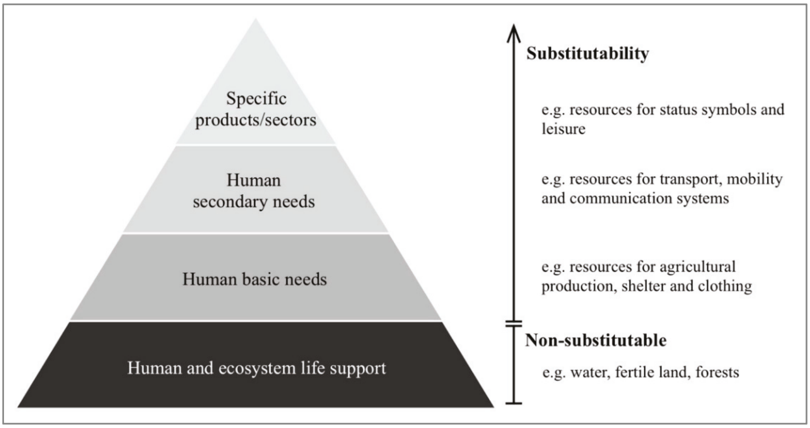

Figure 3. Prioritization of natural resource needs adapted from Mancini et al. [44].

A second aspect raised in some of the reviewed documents was the need to interpret the criticality of natural resources as dynamic, as it is not an inherent property of a resource [1,54]. Rather, the "state of being critical" [33] will evolve over time, for example, due to technological innovations, geopolitical changes, or climate change. Lastly, some articles discuss the importance of assessing the criticality of a certain natural resource relative to other ones (or to other interest groups or through time), as opposed to selecting an arbitrary threshold to divide critical and noncritical resources, e.g., [66].

3.4. Aspects of Criticality

As introduced in Figure 2, the concept of criticality contains different aspects captured by the subcodes. There were 773 in total, with the majority of the codes (22%) related to economic aspects of criticality. Technical aspects were second in line (15% of codes), physical availability as well as environmental aspects each accounted for 11%, political aspects of criticality were covered by 10% of the codes, and strategic aspects by 6%. Finally, sociohuman aspects and holistic approaches to criticality accounted for the rest (4% of the codes).

Thus, economic criticality concerns were most frequently discussed. Two of the main topics under economic aspects were risks of supply disruption and the ensuing economic consequences. The latter was also referred to as economic importance or vulnerability. Economic characteristics of natural resources mentioned as part of one or both of these topics included, for example: current and future supply and demand trends [7,40,63], price increases and volatility [39], competing demands [64], sensitivity of the relevant value chains [67], and consumption level [36]. Frenzel et al. [59] (p. 2), state that "most criticality assessments focus exclusively on economic aspects in their practical implementation". We would argue that this economic inclination is at the expense of other values and functions of the natural resources at risk. An underlying assumption seems to be that as long as economic interests are ensured, societal well-being will also be achieved.

Regarding technological aspects of criticality, continuous technological development changes the demand for natural resources, for example, emerging clean energy technologies which require rare earth metals and new bio-based materials that need algae [42,68]. A frequently mentioned aspect of these technological demand dynamics is the availability and performance of substitutes (e.g., [7]). Yet, as mentioned earlier, [17,22,50] counter these concerns by stating that only resources that perform life and ecosystem support functions are nonsubstitutable, represented in the base layer of Mancini et al.'s [44] prioritization pyramid of resource needs (Figure 3). Furthermore, technological development can enhance the efficiency of natural resource use and, thereby, reduce their criticality, for example, increased agricultural yield or extraction potential [69]. Recycling is a major topic related to this, complemented by the possibilities of reduction, reuse, and recovery [33]. The literature on this aspect was oriented towards non-renewables in industry. Yet, this argument could also apply to renewable resources. We recognise that technology, with its influence on both demand and supply, is closely interconnected with economic aspects. In general, innovation is seen as important to reduce the criticality of resources.

Physical availability or scarcity of natural resources is mentioned often in the criticality debate (11%). For non-renewable resources, its reserves are often compared to annual consumption or production rates, resulting in its remaining lifetime or depletion time. In general, many authors claim that the extent of natural resource stocks is less important to criticality than accessibility, which is rather defined by geopolitical and socioeconomic conditions [70–72]. This is partly due to uncertainties in reserve estimates and because criticality is often analysed on a shorter timescale than the depletion time of the resources being considered [5,55,73]. However, [74] showed that decreasing ore grades globally have required increasing amounts of energy for extraction. This trend is generally expected to continue with the discovery of new reserves [75]. Still, there is uncertainty about projected resource availability and the energy needed for extraction because of imprecise or lacking data and technological advances in prospecting, mining, recycling, and energy efficiency [75].

When considering renewable energy resources, innovation and transformation to a renewable energy system requires many non-renewable, mined resources [76]. Hence, the physical availability of renewable and non-renewable resource stocks is closely linked. The importance of physical availability has mainly been debated in relation to non-renewable and energy resources. However, when considering conditionally renewable resources, the necessity to maintain a certain level of resource stock for it to be able to renew itself and provide life and ecosystem support functions is emphasized [4]. We argue that more emphasis should be placed on the biophysical reality of renewable and non-renewable stocks for criticality considerations as compared to the economic concerns over stocks, such as yearly production rates.

When considering environmental aspects of criticality, the main topics discussed are the environmental side-effects of natural resource extraction and production on human health, ecosystems and their biodiversity, or the climate [77]. Some argue that good environmental standards and regulations in the resource's country of origin could lower the risk for supply disruption and, consequently, lower the criticality of the resource [5,65,72]. However, [78] (p. 587), interpreted the European Commission's [5] report differently. They believe the resource's criticality will increase with "stricter environmental regulation in an exporting country impairing imports of a resource type". Most authors refer to environmental impacts and regulations without exactly stating how they might impact the criticality of the resource. Lastly, some publications also mention that the degradation of conditionally renewable resources can cause them to become critical, namely, when the ecological carrying capacity is exceeded and the resources lose their ability to renew themselves or perform their regulatory functions [44,78].

Another clear theme within natural resource criticality is political concerns. The largest concern is the low quality of governance or political instability in the supplying countries, in combination with the high geographical concentrations of resources in those countries [71]. Schillebeeckx [79] calls this situation "politically scarce", where higher possibilities for political or social unrest might disrupt the supply of the resource. Bedder [6] is one of the few who mention corporate concentration as well as country concentration that can increase criticality due to oligopolistic market imbalances. Consequently, net import reliance and trade relationships can significantly impact the criticality of a resource: export restrictions and quotas in supplying countries increase the criticality, while trade agreements lower criticality for importing countries [7,8]. This way of comprehending export quota and trade agreements indicates to us that the concept of criticality is mainly used by and applied to importing, industrialized, Western countries. Export quota would protect the exporting country from losing access to its own critical natural resources and are thus only considered negative for countries that rely heavily on imports.

Further, [50] consider criticality evaluations a "political process" and others agree that the criticality of natural resources is influenced by the "prevailing political vision", as the concept is largely used in governmental and consulting reports with the purpose of informing decision-making [33,36,80]. Our review (Figure 2) shows that the discussion is now more balanced by numerous scientific publications critiquing and contributing to the concept. Nonetheless, we can argue that the main interest is still political and that information is gathered to inform decision-making. Additionally, we would argue that the dominance of the initial defence aspects and the current economic inclination around the concept are an artefact of its political roots.

Strategic concerns of critical natural resources are closely related to political aspects and power over resources. Currently, "strategy" is not a dominant aspect of the criticality discourse (Figure 2). Most authors, almost exclusively, relate "strategic" to military and defence needs, as part of an overall criticality concept [5,39,40]. Now, strategic concerns are also attributed to another interest group than governments: namely, businesses [43]. The term "strategic", as well as "critical", has gone through a substantial expansion and transition over time. Haglund [3] explains that this is common for political concepts due to changing societal conditions and contested interpretations of the concept and, thus, does not consider it useful to define it. Despite the tendency of political concepts to change their meaning over time, we suggest authors clearly define what they mean by the term "critical natural resources". Without proper definitions and conceptualisations in a majority of the reviewed publications, it is difficult to compare the use of the concept, even more so due to its multidisciplinary character. Only through discussions and debate of these multidisciplinary concepts can we deepen our understanding of the problems we are trying to comprehend and continue to build up (and upon) scientific knowledge from a collaboratively created body of literature [11].

The final two identified aspects of criticality are infrequently mentioned: sociohuman aspects and a holistic or integrated view. Regarding sociohuman aspects, some publications make a link between criticality and inadequate social conditions during extraction of resources and related regulations, such as human rights violations, resource conflicts, illicit trade, and precarious working conditions [44]. We discovered an inconsistency and ambiguity in the literature on whether regulations to protect employees, local inhabitants, and the environment from negative impacts of extraction processes increase or decrease the criticality of that resource (e.g., [8] vs. [81]). The inclusion of social and environmental regulation into evaluations of criticality shows an interest in broadening the debate from purely economic interests towards including social and environmental concerns.

Furthermore, only a handful of publications mention the sociocultural value of natural resources (e.g., [21]). The publications acknowledge that resources have important economic, life-support, and ecological functions. However, they do not recognise their immaterial sociocultural functions, such as physical and mental health, education, identity (heritage value), freedom, and spiritual values, that increase the general well-being of human society [21].

Despite the dominant economic and geopolitical interpretations of resource criticality, the above overview and several of the publications in the review demonstrate that criticality is determined by an interaction of many factors. They include economic, technological, physical availability, environmental, political, strategic, and social aspects of the concept [4,44,50,57,80]. Therefore, some authors plea for a more challenging, interdisciplinary approach to explore sustainable options for natural resource use, acknowledging and comprehending the dynamic interplay between all these aspects [21,44,82]. Nevertheless, [2] warn for the paradox of comprehensiveness versus accuracy. We do not agree with claims made by, for example, [3,81], that a broad aggregate concept of criticality would make it practically useless or inaccurate. Risks are everywhere. Only accounting for certain aspects of risks to natural resources while leaving other aspects behind is a distortion of the information that serves as a basis upon which natural resource policies are built. A clear specification is needed of which functions of a natural resource are threatened and in what way (e.g., economic, sociocultural or life, and ecosystem support functions). Mancini et al.'s [44] ranking of importance between the different functions of natural resources (Figure 3) is useful for that purpose.

Thus, overall, we found a dominance of the economic aspect of criticality. Furthermore, we identified an under-representation of the importance of physical availability, uncertainty on how to incorporate environmental and social impacts, as well as a dominant Western perspective. The political roots and goals of the concept steered its conceptualisations towards defence and, later, economic aspects. We suggest that there is a need for a holistic, integrated concept of criticality for natural resources, open to different value orientations regarding natural resources to balance the uncovered perspectives. Possible methodological limits in reaching these findings are discussed in Section 3.5 before reaching our conclusions.

3.5. Criticality Assessments

It is not our goal to give a full review of natural resource criticality assessment methodologies, especially considering the number of existing reviews of the topic (e.g., [59]). However, an extensive analysis of the criticality discourse cannot be done without touching upon them, since they are the main way of application and communication of the concept.

3.5.1. The Tools of Criticality Assessments

Several types of tools exist for quantifying and communicating natural resource criticality. They most often include detailed time series and scenario analyses per natural resource or hierarchical risk ranking based on indicator selection and aggregation [62]. The criticality matrix is most often applied, locating various resources as dots between two dimensions or axes of basic risk theory: (1) the probability of a disruption in the resource supply, often termed "supply risk" and (2) the impact caused by such a constraint, termed "vulnerability" [72,83]. The overall risk is the product of these two dimensions, creating hyperbolic contours of constant criticality within the plot [40]. However, these axes are often modified to the extent of losing the connection with risk theory, for example, by changing the terminology and indicators of the axes or by adding or omitting an axis [50,57,59]. Thus, when selecting indicators for a criticality matrix, attention and strictness are required to avoid using vague or ambiguous terminology of the axes.

Furthermore, the more methodologically oriented publications in the review showed that criticality assessments need to be directed towards a specific interest group [66] and timescale [81]. They should also be relative to other contexts, such as other resources, spatial, or timescales [66,84]. Additionally, periodic re-evaluations are required when a static tool is used to assess the dynamic and evolving state of resources [67,82]. It is important to highlight that these considerations are exactly the same ones as mentioned before as important parts of the definition of criticality for natural resources.

3.5.2. A Predominance of Non-Renewable Resources in Criticality Assessments

The scope of natural resources considered in criticality assessments is mainly limited to minerals or, even more narrowly, to metals [5,36,67,77,85]. According to [36] (p. 7620), "supply risks of fossil fuels and their impacts on economies have been examined for decades, only in recent years have studies appeared that evaluate the criticality of a broad set of nonfuel minerals". Also, in Table 2, 9 of the 24 criticality definitions relate specifically to materials (i.e., minerals and metals). Graedel and Reck [66] (p. 696), contend that it is desirable for evaluations to be "broad in terms of elements addressed". A plausible explanation is that the language used to describe shortages in renewable resources has been expanding to other concepts than solely criticality. Many conditionally renewable resources can become scarce or critical if their management is unsustainable. Therefore, concepts linking to sustainability thinking—such as sustainable yield, used in [86], sustainable natural resource management, used in [87], and resource governance, used in [88,89]—could add to the debate on criticality of renewable resources without being captured in our systematic literature review.

We would argue that there are possibilities to broaden the scope of natural resources discussed in criticality debates and assessments by explicitly including renewable resources. This has been shown in assessments by Chapman et al. [35] of natural rubber, pulpwood, and soft sawnwood for the European Commission's report [73] and by Sonderegger et al. [90] of water. Additionally, de Groot et al. [50] developed a framework to assess the criticality of renewable resources, although no applications of it were found. Generally, these approaches correspond to the more common criticality matrices for minerals based on risk theory, with the modification or addition of some indicators. The four abovementioned research documents show that a holistic approach to criticality evaluations of natural resources is possible and that it is not necessary to separate renewables and non-renewables or to do so in their terminology: natural capital and materials, such as minerals and metals, as in Table 2.

Moreover, we argue for the need to widen the scope of natural resources included in criticality assessments. Renewable resources perform the main functions necessary for basic life and ecosystem support, located at the base of Mancini et al.'s [44] resource prioritization pyramid for human needs (Figure 3). Klinglmair et al. [78] (p. 586) agree that "impacts on the carrying capacity of ecosystems and their intrinsic capability of renewal may lead to impact on human needs and life greater than shortage in, e.g., mineral resources". The relative level of criticality can only be established per resource and compared among them when a criticality analysis incorporates a wide array of natural resources. Most of the pyramid's basic functions (Figure 3) are not valued within economic markets. Consequently, even if renewable natural resources are incorporated into the mainstream criticality assessments, the natural resources most critical to humanity will probably be overlooked as current analyses are mainly based on economic arguments and indicators.

Overall, we need to be aware that criticality assessments have communicative power and can be highly influential when it comes to decision-making, even when the assessment is executed without a rigorous conceptual and theoretical foundation. In order to design policies that ensure sustainable management of natural resources, balanced information is needed. Therefore, we propose that criticality assessments should include two things: first, a wide range of natural resources, including renewables resources along with the traditional non-renewables; second, an evaluation of resource importance based on human needs (e.g., with Mancini et al.'s [44] resource prioritization pyramid (Figure 3)). That includes sociocultural values and life and ecosystem support functions in addition to the standard economic arguments and indicators. If these two conditions are met, we expect other resources, such as clean water, clean air, forests, fertile soil, etc., to have a much higher criticality level relative to certain metals and rare earth minerals that are now commonly considered critical. Consequently, these resources might gain more attention in policy circles.

We consider it appropriate to define a concept before applying it in assessments and methodologies. In the literature we reviewed, only a handful of publications did so, despite the widespread use of resource criticality assessments (Table 2). As a consequence, many of the existing definitions are derived from the assessment methods, instead of the other way around. We argue that a holistic definition of criticality for natural resources, aligned with risk theory, might reduce inconsistencies and increase comparability among assessment methods. This could provide a common basis for balanced information to decision-makers while opening up to various value orientations for natural resources.

3.6. Proposal for a Holistic Definition

As mentioned in the beginning of this paper, definitions of critical natural resources were presented within academic disciplines that only engaged in cooperation or debate to a limited extent, for example, the clear division between definitions of critical materials and critical natural capital (Table 2). Nonetheless, the information gathered on a definition of "critical" for natural resources indicates common ideas of the concept: both an aspect of uncertainty or threat, as well as importance. These keywords relate directly to the two dimensions of risk according to standard risk theory and analyses [83]. Although this might be an artefact of creating definitions based on the tools used for criticality assessments, risk theory brings fundamental understanding to the concept of criticality. Therefore, we see it fitting to align our definition with risk theory. Simultaneously, risk analyses frameworks provide a foundation for criticality assessments.

We propose the following, generally applicable, definition of criticality for natural resources, which is an adaptation of the Oxford Dictionary [60] definition:

Criticality is a relative and dynamic state of a natural resource:

(a) of decisive importance, ranked according to a hierarchy of human needs, in relation to the issue or interest group specified, and
(b) attended with uncertainty or a threat.

We argue that this definition is aligned with risk theory [83] because of its two components: importance of the function of this resource, linked to the severity of outcomes of specified objectives, and threat or uncertainty. Moreover, the definition accounts for a specific interest group, timescale, and the dynamic and relative character of criticality, all previously mentioned as important for definitions and assessments of criticality. By relative, we mean a resource cannot be critical in itself, but that additional perspectives need to be addressed. For example, a resource should be relative to itself through time or to other resources at the same time. Local perspectives can be compared to the global scale. Criticality could also be relative from one place to another or from the perspective of one population group to another.

This definition allows for and encourages a holistic understanding of natural resource criticality. Firstly, by allowing for the perspectives, values, and assessments from any kind of interest group (i.e., also global, local, and non-Western perspectives). Secondly, it can be applied to renewable as well as non-renewable resources, preferably to both at the same time (i.e., within a wide array of natural resources). Lastly, we propose that the resource's importance should be explicitly ranked according to a hierarchy of human needs (e.g., Mancini et al.'s [44] resource prioritization (Figure 3)). Thereby, we suggest that the criticality of a resource increases when moving down the pyramid to basic human needs. Another less instrumental way of establishing a hierarchy of resource needs could be based on relational value frameworks, as advocated by Castleden [18]. Both allow to lessen the dominance of economic interests over other sociocultural and life-support values of natural resources. That way, the proposed definition of criticality could ensure more balanced information in criticality assessments and policy recommendations. We invite those who are interested to comment, contest, and develop our proposed definition.

Before summarizing our conclusions, we would like to point the reader to some of the recent literature within and outside of our review that does approach critical natural resources from the more neglected perspectives. Criticality of renewables have been assessed for water [90] and soils [91]. Moreover, this latter reference provides a more global perspective by teaming up authors from Kenya, the United States, Ghana, the United Kingdom, Argentina, Italy, Germany, and Denmark. Chiesura and de Groot [21] introduced critical sociocultural functions of renewable resources. Even though political science, psychology, sociology, ethics, and other social sciences are more and more present in natural resource research, we have not encountered any thorough social science scholarship that engages with concepts of resource criticality.

Lastly, there are some limitations in our methodology and analysis which carry forward into the presented understanding of the concept of "critical natural resources". First, the systematic literature search was limited to English documents. This could partly explain the lack of non-Western publication, for example, from Africa, Asia, and Latin America. Hamel [92] states that 75% of international scientific periodical literature in social sciences and 90% in natural sciences is published in English. Consequently, we can assume to have captured the international scientific literature while probably missing out on non-English national scientific journals, books, and reports. Another disadvantage of our search strategy is that grey literature, such as books and reports, are more difficult to systematically discover because they are not gathered in large publicly available databases like scientific journal articles are. This means that in our data, scientific perspectives probably prevail over practitioners' knowledge. Further, in our search string (see Appendix A), we accounted for the terms "resource", "material", and "natural capital" in relation to criticality. There are more terms describing natural resources that we did not include, such as "environmental assets" and "ecosystem services". From our preparatory literature research, these terms did not occur frequently in combination with criticality. Additionally, they are explicitly part of definitions of natural capital [93]. Likewise, we assumed other terms for "natural resources" were largely covered by the included terms.

4. Conclusions

The discourse around critical natural resources ascribes certain resources to be more critical than others and provides management guidance for them. By doing so, the discourse has a large influence on decision-making regarding natural resources. Diverging understandings of criticality for natural resources consequently lead to different policy outputs. Therefore, we set out to analyse the main understandings and underlying assumptions captured in the criticality debate on natural resources. By systematically mapping out the discourse, we did not come upon one generally accepted definition of the concept. Aspects commonly brought up as contributing to resource criticality were: economic, technological, physical availability, environmental, political, and, to a minor extent, sociohuman and holistic perspectives.

We identified several trends in the interpretation and use of the concept. First and foremost, economic concerns dominate the discourse on natural resource criticality at the expense of other values and functions, especially since the economic crisis of 2008. We argue for the need to balance out resource criticality considerations with more emphasis on the biophysical reality of natural resource stocks. Especially for those that provide nonsubstitutable life and ecosystem support functions. Sociocultural values of natural resources to human well-being should also be given more attention.

Secondly, published material about the topic comes mainly out of Western countries and, throughout our reading, we did not come across a standpoint on the topic from the Global South. Third, there is a clear distinction between the two main scientific branches that describe criticality, that is, ecologically versus industrially oriented disciplines. Moreover, social sciences, except for economics, are largely missing from the debate. Lastly, the majority of criticality studies solely focus on non-renewable resources, such as minerals and metals, without considering renewable resources. This could be the result of renewable resources and their criticality being discussed with different terminology not captured within this study. We, however, advocate for taking renewable resources further into account when discussing criticality and have questioned the usefulness of a distinct non/renewable split in the discourse. In sum, we addressed the need to broaden the scope of the criticality discourse to include more perspectives, scientific disciplines, and types of natural resources.

Based on this review, we developed a holistic definition of criticality for natural resources. We argue that the expansion of the criticality concept does not make it redundant. Rather, a holistic approach is necessary to provide decision-makers with neutral and balanced information and recommendations on natural resource management.

Further research possibilities include an analysis of non-English documents on the topic to address the main methodological limitation of this review. Secondly, it would be interesting to investigate how the development of the criticality concept for natural resources links to developments in sustainability thinking. Specifically, the hypothesis came up that there is a broader language to describe crisis situations for renewables than for non-renewables, which could have led to the over-representation of non-renewables in criticality assessments compared to renewables. Lastly, a streamlined methodology for criticality assessments could be developed based on the proposed definition of criticality for natural resources.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A Literal Search Strings Applied to the Scientific Literature Databases

The developed search string for Web of Science:

("natural resource")*
AND (("critic" OR "strategic" OR "key") NEAR/20 ("resourc*" OR "material*" OR "natural capital"))*
AND (("defin" OR "categor*" OR "classif*" OR "typology" OR "character*" OR "properties") NEAR/20 ("resourc*" OR "material*" OR "natural capital"))*

The developed search string for Scopus, approaching the previous syntax as much as possible:

KEY ("natural resource")*
AND TITLE-ABS-KEY ((("critic" OR "strategic" OR "key") PRE/20 ("resource*" OR "material*" OR "natural capital"))*
OR (("resource" OR "material*" OR "natural capital") PRE/20 ("critic*" OR "strategic" OR "key")))*
AND TITLE-ABS-KEY ((("defin" OR "categor*" OR "classif*" OR "typology" OR "character*" OR "properties") PRE/20 ("resource*" OR "material*" OR "natural capital"))*
OR (("resource" OR "material*" OR "natural capital") PRE/20 ("defin*" OR "categor*" OR "classif*" OR "typology" OR "character*" OR "properties")))*

Appendix B

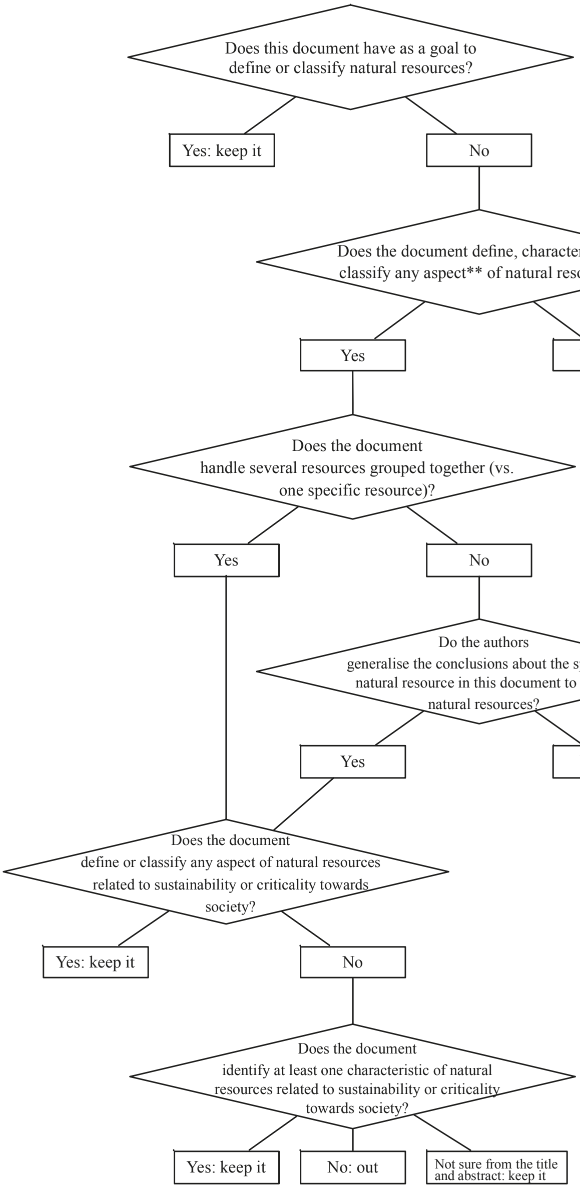

Figure A1. Inclusion and exclusion criteria for the selection of documents into the review. * with characterize, we mean identify characteristics or properties. ** any aspect of natural resources (e.g., resource use, management, production, extraction, impacts, etc.).

Appendix C

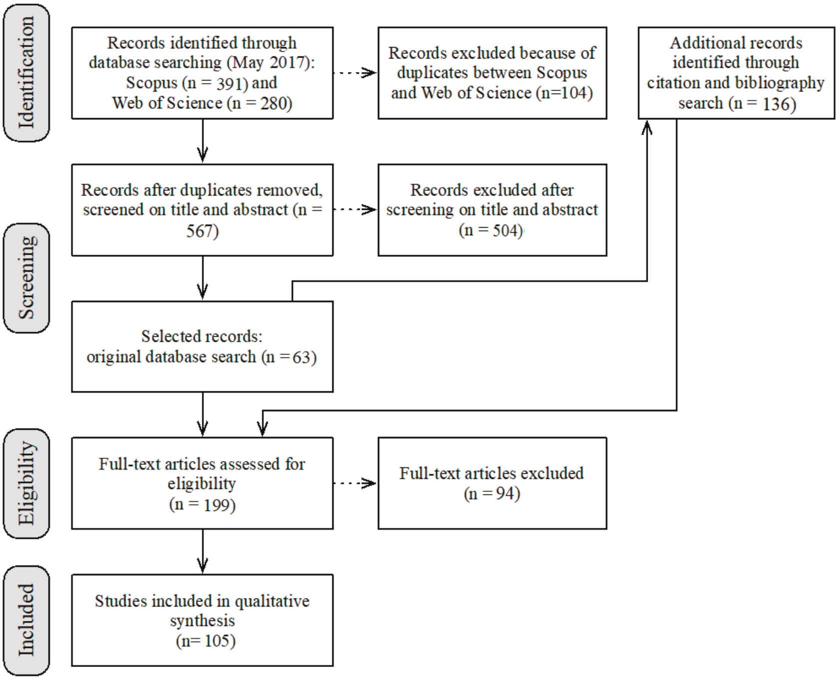

Figure A2. Flow diagram indicating the number of documents in each selection step of document gathering for the review.

Appendix D

Table A1. A list of all reviewed publications.

nr.	Authors	Year	Title	Journal
1	Achzet, B., and Helbig, C.	2013	How to evaluate raw material supply risks—an overview	Resources Policy
2	Andersen, A. D.	2012	Towards a new approach to natural resources and development: the role of learning, innovation and linkage dynamics	Int. J. Technological Learning, Innovation and Development
3	APS Panel on Public Affairs (POPA) & the Materials Research Society (MRS)	2011	Energy Critical Elements: Securing Materials for Emerging Technologies	Report
4	Armstrong, C.	2017	Justice and Natural Resources: An Egalitarian Theory	Book
5	Bach, V., Berger, M., Finogenova, N., and Finkbeiner, M.	2017	Assessing the Availability of Terrestrial Biotic Materials in Product Systems (BIRD)	Sustainability
6	Bach, V., Berger, M., Henssler, M., Kirchner, M., Leiser, S., Mohr, L., Rother, E., Ruhland, K., Schneider, L., Tikana, L., Volkhausen, W., Walachowicz, F., and Finkbeiner, M.	2016	Integrated method to assess resource efficiency—ESSENZ	Journal of Cleaner Production
7	Bedder, J.C.M.	2015	Classifying critical materials: a review of European approaches	Applied Earth Science

Table A1. *Cont.*

nr.	Authors	Year	Title	Journal
8	Bell, J.E., Autry, C.W., Mollenkopf, D.A., and Thornton, L.M.	2012	A Natural Resource Scarcity Typology: Theoretical Foundations and Strategic Implications for Supply Chain Management	Journal of Business Logistics
9	Blengini, G.A., Nuss, P., Dewulf, J., Nita, V., Peirò, L.T., Vidal-Legaz, B., Latunussa, C., Mancini, L., Blagoeva, D., Pennington, D., Pellegrini, M., Van Maercke, A., Solar, S., Grohol, M., and Ciupagea, C.	2017	EU methodology for critical raw materials assessment: Policy needs and proposed solutions for incremental improvements	Resources Policy
10	Brand, F.	2009	Critical natural capital revisited: Ecological resilience and sustainable development	Ecological Economics
11	Bridge, G.	2009	Material Worlds: Natural Resources, Resource Geography and the Material Economy	Geography Compass
12	Buchert, M., Schüler, D., and Bleher, D.	2009	Critical metals for future sustainable technologies and their recycling potential	Report
13	Buijs, B., and Sievers, H.	2011	Critical Thinking about Critical Minerals: Assessing risks related to resource security	Briefing or working paper
14	Buijs, B., Sievers, H., and Espinoza, L.A.T.	2012	Limits to the critical raw materials approach	Waste and Resource Management
15	Castleden, H.	2009	Rethinking Key Concepts: A precursor to rethinking environmental management	Environments Journal Volume
16	Chakhmouradian, A.R., Smith, M.P., and Kynicky, J.	2015	From "strategic" tungsten to "green" neodymium: A century of critical metals at a glance	Ore Geology Review
17	Chapman, A., Arendorf, J., Castella, T., Thompson, P., Willis, P., Espinoza, L.T., Klug, S., and Wichmann, E.	2013	Study on Critical Raw Materials at EU Level	Report
18	Chiesura, A., and de Groot, R.	2003	Critical natural capital: a sociocultural perspective	Ecological Economics
19	Ciacci, L., Nuss, P., Reck, B.K., Werner, T.T., and Graedel, T.E.	2016	Metal Criticality Determination for Australia, the US, and the Planet—Comparing 2008 and 2012 Results	Resources
20	Cimprich, A., Young, S.B., Helbig, C., Gemechu, E.D., Thorenz, A., Tuma, A., and Sonnemann, G.	2017	Extension of geopolitical supply risk methodology: Characterization model applied to conventional and electric vehicles	Journal of Cleaner Production
21	Collados, C., and Duane, T.P.	1999	Natural capital and quality of life: a model for evaluating the sustainability of alternative regional development paths	Ecological Economics
22	Cutter, S.L., and Renwick, W.H.	2004	Exploitation, conservation, preservation: a geographic perspective on natural resource use	book, publisher: John Wiley and Sons, USA
23	de Groot, R.S., Wilson, M.A., and Boumans, R.M.J	2002	A typology for the classification, description and valuation of ecosystem functions, goods and services	Ecological Economics
24	de Groot, R., Van der Perk, J., Chiesura, A., and van Vliet, A.	2003	Importance and threat as determining factors for criticality of natural capital	Ecological Economics
25	Deutsch, L., Folke, C., and Skånberg, C.	2003	The critical natural capital of ecosystem performance as insurance for human well-being	Ecological Economics
26	Dewulf, J., Benini, L., Mancini, L., Sala, S., Andrea, Blengini, G., Ardente, F., Recchioni, M., Maes, J., Pant, R., and Pennington, D.	2015	Rethinking the Area of Protection "Natural Resources" in Life Cycle Assessment	Environmental Science & Technology
27	Dewulf, J., Blengini, G.A., Pennington, D., Nussa, P., and Nassar, N.T.	2016	Criticality on the international scene: Quo vadis?	Resources Policy

Table A1. *Cont.*

nr.	Authors	Year	Title	Journal
28	Dewulf, J., Mancini, L., Blengini, G.A., Sala, S., Latunussa, C., and Pennington, D.	2015	Toward an Overall Analytical Framework for the Integrated Sustainability Assessment of the Production and Supply of Raw Materials and Primary Energy Carriers	Journal of Industrial Ecology
29	Drost, D., and Wang, R.	2015	Rare earth element criticality and sustainable management	Conference proceedings
30	Edwards, V., and Steins, N.	1999	A framework for analysing contextual factors in common pool resource research	Journal of Environmental Policy & Planning
31	Ekins, P.	2003	Identifying critical natural capital: Conclusions about critical natural capital	Ecological Economics
32	Ekins, P., Folke, C., and De Groot, R.	2003	Identifying critical natural capital (editorial)	Ecological Economics
33	Ekins, P., Simon, S., Deutsch, L., Folke, C., and De Groot, R.	2003	A framework for the practical application of the concepts of critical natural capital and strong sustainability	Ecological Economics
34	England, R.W:	1998	Should we pursue measurement of the natural capital stock?	Ecological Economics
35	EU Commission	2010	Critical raw materials for the EU: Report of the Ad-hoc Working Group on defining critical raw materials	Report
36	EU Commission	2014	Report on Critical Raw Materials for the EU: Report of the Ad hoc Working Group on defining critical raw materials	Report
37	Fischer-Kowalski, M., Krausmann, F., Giljum, S., Lutter, S., Mayer, A., Bringezu, S., Moriguchi, Y., Schütz, H., Schandl, H., and Weisz, H.	2011	Methodology and Indicators of Economy-wide Material Flow Accounting: State of the Art and Reliability Across Sources	Journal of Industrial Ecology
38	Folke, C., Hammer, M., Costanza, R., and Jansson, A.	1994	Investing in Natural Capital—Why, What, and How?	Book chapter in: Investing in Natural Capital—The Ecological Economics Approach to Sustainability
39	Frenzel, M., Kullik, J., Reuter, M.A., and Gutzmer, J.	2017	Raw material 'criticality'—sense or nonsense?	Journal of Physics D: Applied Physics
40	Gemechu, E.D., Helbig, C., Sonnemann, G., Thorenz, A. and Tuma, A.	2016	Import-based Indicator for the Geopolitical Supply Risk of Raw Materials in Life Cycle Sustainability Assessments	Journal of Industrial Ecology
41	George, G., Schillebeeckx, S.J.D., and Liak, T.L.	2015	The management of natural resources: an overview and research agenda	Academy of Management Journal
42	Glöser-Chahoud, S., Espinoza, L.T., Walz, R. and Faulstich, M.	2016	Taking the Step towards a More Dynamic View on Raw Material Criticality: An Indicator Based Analysis for Germany and Japan	resources
43	Glöser, S.	2012	Quantitative Analysis of the Criticality of Mineral and Metallic Raw Materials Based on a System Dynamics Approach	Conference proceedings
44	Glöser, S., Espinoza, L.T., Gandenberger, C., and Faulstich, M.	2015	Raw material criticality in the context of classical risk assessment	Resources Policy
45	Erdmann, L., and Graedel, T.E.	2011	Criticality of Non-Fuel Minerals: A Review of Major Approaches and Analyses	Environmental Science & Technology
46	Graedel, T.E., and Nassar, N.T.	2013	The criticality of metals: a perspective for geologists	Geological Society, London, Special Publications
47	Graedel, T.E., Gunn, G., and Espinoza, L.T.	2014	Metal resources, use and criticality	Book Chapter in: Critical Metals Handbook
48	Graedel, T.E., Barr, R., Chandler, C., Chase, T., Choi, J., Christoffersen, L., Friedlander, E., Henly, C., Jun, C., Nassar, N.T., Schechner, D., Warren, S., Yang, M., and Zhu, C.	2012	Methodology of Metal Criticality Determination	Environmental Science & Technology

Table A1. *Cont.*

nr.	Authors	Year	Title	Journal
49	Graedel, T.E., and Reck, B.K.	2015	Six Years of Criticality Assessments: What Have We Learned So Far?	Journal of Industrial Ecology
50	Graedel, T.E., Harper, E.M., Nassar, N.T., Nuss, P., and Reck, B.K.	2015	Criticality of metals and metalloids	Proceedings of the National Academy of Sciences
51	Habib, K., and Wenzel, H.	2016	Reviewing resource criticality assessment from a dynamic and technology specific perspective—Using the case of direct-drive wind turbines	Journal of Cleaner Production
52	Habib, K., Hamelin, L., Wenzel, H.	2016	A dynamic perspective of the geopolitical supply risk of metals	Journal of Cleaner Production
53	Haglund, D.G.	1984	Strategic minerals: A conceptual analysis	Resources Policy
54	Hallstedt, S.I., and Isacsson, O.	2017	Material criticality assessment in early phases of sustainable product development	Journal of Cleaner Production
55	Hanna, S., Folke, C., and Mäler, K.	1995	Property Rights and Environmental Resources	Book Chapter in: Property Rights and the Environment—Social and Ecological Issues
56	Hanna, S., Folke, C., and Mäler, K.	1996	Rights to Nature: Ecological, Economic, Cultural, and Political Principles of Institutions for the Environment	Book, publisher: Island Press
57	Helbig, C., Wietschel, L., Thorenz, A., and Tuma, A.	2016	How to evaluate raw material vulnerability—An overview	Resources Policy
58	Hennebel, T., Boon, N., Maes, S., and Lenz, M.	2015	Biotechnologies for critical raw material recovery from primary and secondary sources: R&D priorities and future perspectives	New Biotechnology
59	Jacobson, D.M., Turner, R.K., and Challis, A.A.L.	1988	A reassessment of the strategic materials question	Resources Policy
60	Jin, Y., Kim, J., and Guillaume, B.	2016	Review of critical material studies	Resources, Conservation and Recycling
61	Jowsey, E.	2007	A new basis for assessing the sustainability of natural resources	Energy
62	Jowsey, E., and Kellett, J.	1995	The comparative sustainability of resources	International Journal of Sustainable Development & World Ecology
63	Klinglmair, M., Sala, S., and Brandão, M.	2014	Assessing resource depletion in LCA: a review of methods and methodological issues	International Journal of Life Cycle Assessment
64	Knoeri, C., Wäger, P.A., Stamp, A., Althaus, H.J., and Weil, M.	2013	Towards a dynamic assessment of raw materials criticality: Linking agent-based demand—With material flow supply modelling approaches	Science of the Total Environment
65	Le Billon, P.	2014	Wars of Plunder: Conflicts, Profits and the Politics of Resources	Book
66	Lloyd, S., Lee, J., Clifton, A., Elghali, L., and France, C.	2012	Recommendations for assessing materials criticality	Waste and Resource Management
67	Lujala, P.	2003	Classification of natural resources	Unpublished manuscript, available at Researchgate
68	MacDonald, D.V., Hanley, N., and Moffatt, I.	1999	Applying the concept of natural capital criticality to regional resource management	Ecological Economics
69	Malinauskien, M., Kliopova, I., Slavickait, M., and Staniskis, J.K.	2016	Integrating resource criticality assessment into evaluation of cleaner production possibilities for increasing resource efficiency	Clean Technologies and Environmental Policy
70	Mancini, L., Sala, S., Recchioni, M., Benini, L., Goralczyk, M. and Pennington, D.	2015	Potential of life cycle assessment for supporting the management of critical raw materials	International Journal of Life Cycle Assessment
71	Mancini, L., Benini, L., and Sala, S.	2016	Characterization of raw materials based on supply risk indicators for Europe	International Journal of Life Cycle Assessment
72	National Research Council	2008	Minerals, Critical Minerals, and the U.S. Economy	Report

Table A1. *Cont.*

nr.	Authors	Year	Title	Journal
73	O'Neill, D.W.	2015	What Should Be Held Steady in a Steady-State Economy? Interpreting Daly's Definition at the National Level	Journal of Industrial Ecology
74	Oxford English Dictionary Online	2017	critical, adj.	Oxford English Dictionary Online
75	Oxford English Dictionary Online	2017	criticality, n.	Oxford English Dictionary Online
76	Oxford English Dictionary Online	2017	natural, adj. and adv.	Oxford English Dictionary Online
77	Oxford English Dictionary Online	2017	resource, n.	Oxford English Dictionary Online
78	Peck, D., Kandachar, P., and Tempelman, E.	2015	Critical materials from a product design perspective	Materials and Design
79	Pelenc, J., and Ballet, J.	2015	Strong sustainability, critical natural capital and the capability approach	Ecological Economics
80	Pessoa, A., and Silva, M.R.	2009	Environment based innovation: Policy questions	Finisterra
81	Gabriela-Cornelia, P.	2008	Evaluation method of natural resources sustainability	Bulletin of the University of Agricultural Sciences & Veterinary Medicine Cluj-Napoca. Agriculture
82	Pretty, J.	2003	Social Capital and the Collective Management of Resources	Science
83	Purnell, P., Dawson, D., Roelich, K.E., Steinberger, J.K., and Busch, J.	2013	Critical materials for infrastructure: local vs. global properties	Conference proceedings
84	Roelich, K., Dawson, D.A., Purnell, P., Knoeri, C., Revell, R., Busch, J., and Steinberger, J.K.	2014	Assessing the dynamic material criticality of infrastructure transitions: A case of low carbon electricity	Applied Energy
85	Rosenau-Tornow, D., Buchholz, P., Riemann, A., and Wagner, M.	2009	Assessing the long-term supply risks for mineral raw materials—a combined evaluation of past and future trends	Resources Policy
86	Schillebeeckx, S.J.D, and George, G.	2013	The Scarcity of Natural Resources and its Organizational Implications: A Review and Conceptual Framework	Briefing or working paper
87	Schneider, L., Berger, M., Schüler-Hainsch, E., Knöfel, S., Ruhland, K., Mosig, J., Bach, V., and Finkbeiner, M.	2014	The economic resource scarcity potential (ESP) for evaluating resource use based on life cycle assessment	International Journal of Life Cycle Assessment
88	Speirs, J., Houari, Y., and Gross, R.	2013	Materials Availability: Comparison of material criticality studies—methodologies and results	Briefing or working paper
89	Speirs, J., McGlade, C., and Slade, R.	2015	Uncertainty in the availability of natural resources: Fossil fuels, critical metals and biomass	Energy Policy
90	Stavins, R.N.	2011	The Problem of the Commons: Still Unsettled after 100 Years	American Economic Review
91	Stern, P.C.	2011	Design principles for global commons: natural resources and emerging technologies	International Journal of the Commons
92	Tacconi, L., and Bennett, J.	1995	Economic implications of intergenerational equity for biodiversity conservation	Ecological Economics
93	UN	2004	United Nations Framework Classification for Fossil Energy and Mineral Resources	Report
94	US bureau of mines	1980	Principles of a Resource/Reserve Classification for Minerals	Report
95	US department of Energy	2010	Critical Materials Strategy	Report
96	Senate and House of Representatives of the United States of America in Congress assembled	1984	National Critical Materials Act of 1984	Public Law

Table A1. *Cont.*

nr.	Authors	Year	Title	Journal
97	Senate and House of Representatives of the United States of America in Congress assembled	1980	National Materials and Minerals Policy, Research and Development Act of 1980	Public Law
98	Whalen, K., and Peck, D.	2014	In the Loop—Sustainable, Circular Product Design and Critical Materials	International Journal of Automation Technology
99	Winterstetter, A., Laner, D., Rechberger, H., and Fellner, J.	2016	Integrating anthropogenic material stocks and flows into a modern resource classification framework: Challenges and potentials	Journal of Cleaner Production
100	Winterstetter, A., Laner, D., Rechberger, H., and Fellner, J.	2015	Framework for the evaluation of anthropogenic resources: A landfill mining case study Ð Resource or reserve?	Resources, Conservation and Recycling
101	World Trade Organization	2010	World Trade Report 2010: Trade in natural resources	Report
102	Xu, Z., Bradley, D.P., and Jakes, P.J.	1995	Measuring Forest Ecosystem Sustainability: A Resource Accounting Approach	Environmental Management
103	Zimmerman, E.W.	1951	World Resources and Industries: A Functional Appraisal of the Availability of Agricultural and Industrial Materials	book: Harper & Brothers, Publishers, New York
104	Zimmermann, T., and Gößling-Reisemann, S.	2013	Critical materials and dissipative losses: A screening study	Science of the Total Environment
105	Zwahlen, R.	1995	The sustainability of resources versus the sustainability of use: a comment	International Journal of Sustainable Development & World Ecology

Appendix E

Table A2. Clusters of journals in Figure 2.

nr.	Cluster Name	Included Journals (Number of Articles)
1	Ecological Economics	Ecological Economics (13)
2	Industrial production journals	Journal of Cleaner Production (5); Journal of Industrial Ecology (3); Waste and Resource Management (2); Materials and Design (1)
3	Resource journals	Resource Policy (8); Resources (2); Resources, Conservation and Recycling (1)
4	Interdisciplinary sustainability journals	International Journal of Life Cycle Assessment (4); Science of the Total Environment (2); Sustainability (1)
5	Technology journals	Environmental Science and Technology (2); Clean Technologies and Environmental Policy (1); International Journal of Automation Technology (1); New Biotechnology (1)
6	Geology and earth sciences journals	Applied Earth Science (1); Special Publications of the Geological Society, London (1); Ore Geology Review (1)
7	Business and management journals	Academy of Management Journal (1); Journal of Business Logistics (1)
8	Energy journals	Applied Energy (1); Energy Policy (1)
9	Others	Bulletin of University of Agricultural Sciences and Veterinary Medicine Cluj-Napoca. Agriculture (1); Journal of Physics D: Applied Physics (1)

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resources

MDPI

Article

Environmental and Social Pressures in Mining. Results from a Sustainability Hotspots Screening

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Abstract: In recent years, increased interest and actions have been taken to better understand, and mitigate, sustainability impacts of mining activities, by both industry and policy. The present work reports on a sustainability hotspots screening performed for the EU Horizon 2020 "Integrated Mineral Technologies for More Sustainable Raw Material Supply" (ITERAMS) project, which foresees a more efficient water recycling, tailings valorization, and minimization of environmental footprint. The focus of this paper is on social and environmental issues in mining. Different methodologies were explored, starting from a qualitative causal loop modelling. Afterwards, an environmental and social LCA screening was performed using well-accepted databases and methods, thus completing results with a literature research. The main findings related to the importance of the supply chain, the vulnerability of local communities, and the toxic emissions from tailings offer a starting point to reflect on the specific social, socio-economic, and environmental context which may influence these issues. A better understanding of the environmental and social pressures associated with mining is not only crucial to orient the sustainability assessment foreseen for the ITERAMS project, but also to contribute in terms of methodology to the challenges tackled by policy and research worldwide towards a more sustainable mining.

Keywords: mining; social impacts; environmental impacts; hotspots; social risks; supply chain; LCA; screening

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1. Introduction

1.1. Mining and the Sustainable Development Goals

A mining activity is defined as "the process of extracting metallic, non-metallic mineral or industrial rock deposits from the Earth" [1]. As reported by the North American Industry Classification System (NAICS), it is often the case that "the term mining is used in the broad sense to include quarrying, well operations, beneficiating (e.g., crushing, screening, washing, and flotation), and other preparation customarily performed at the mine site, or as a part of mining activity" [2]. A number of social and environmental risks and impacts may be generated by these activities, hence preventing the sector and, at a broader level, our societies from a sustainable development, often quoted as the "development that meets the needs of the present, without compromising the ability of future generations to meet their own needs" [3].

In recent years, the mining industry has acknowledged its potential and duty to monitor and assess the sustainability of the raw materials sector, which is referred to the "key enablers of many critical sectors of the economy" [4], including for instance metals, minerals, and biotic materials. A number of programs and initiatives have been undertaken by the industry to take action on those issues that the mining activities have contributed to create or exacerbate. These issues include health problems, water and air pollution, environmental degradation, and restricted access to material resources for local communities. Both this awareness and proper accountability are crucial as the mining industry has the chance to contribute to the achievement of the Sustainable Development Goals (SDGs) by mitigating environmental and social impacts and creating new opportunities. In fact, the relation between mining and the SDGs has been clearly identified [5].

Considering the implementation of new technologies aiming at an efficient waste water treatment and at the reduction of the land consumption for tailings treatment and storage facilities, mining companies can act towards the SDG6 "Clean Water and Sanitation" and SDG15 "Life on Land". Furthermore, given that a number of ore processing processes, such as crushing and grinding, are highly energy demanding [6], an increase in the energy efficiency of the sector may result in a reduction of the Green House Gas (GHG) emissions, hence in the direction of the SDG7 "Energy Access and Sustainability" and the SDG13 "Climate Action". Regarding social sustainability, the mining industry may help to reduce the unemployment rate and promote the economic growth (SDG3 "Good Health and Well-Being"), and create new social opportunities, fighting inequalities and discrimination (SDG1 "End Poverty", SDG5 "Gender Equality", and SDG10 "Reduce inequalities"). Finally, with reference to the SDG 16 "Peace, Justice, and Strong Institutions", mining companies are called upon to a responsible supply of raw materials, in particular when there is the risk that the trading of minerals finances armed conflicts and corruption. The acknowledgement of this latter issue has led to guidance and regulations to promote due diligence for the supply of conflict minerals [7,8].

1.2. Mining and the European Policy Framework

From this brief introduction, it is clear that the mining sector finds itself under the pressure from the society that asks for resources to sustain its development; on the other side, the public opinion and the societal stakeholder request that the raw materials sourcing is performed following social responsibility along the supply chain and environmental protection. Furthermore, it is expected that the resource provision is pursued within legal national and international frameworks [9].

The European Union (EU) has launched a number of initiatives and policies addressing the main social and environmental issues related to raw materials and promoting the effort towards the SDGs, which are not legally binding. As a foundation for the European Commission (EC) commitment towards sustainability of raw materials and related activities, the Raw Materials Initiative (RMI) was established in 2008 [10] with the intention of securing a sustainable and fair resources supply both within and outside the EU. Furthermore, the provision of secondary raw materials is encouraged through recycling together with a more efficient resource use. Following the RMI, the European Innovation Partnership (EIP) on raw materials was launched in 2012 [11] to gather a number of different stakeholders, including academia, citizens, NGOs, industries, and governments. The EIP has the mission to put into practice the legal framework defined by the RMI by establishing action and monitoring plans. For instance, the Raw Materials Scoreboard (RMS) was implemented in 2016 and updated in 2018 [4] to provide quantitative information to be used by the Partnership and decision-makers to monitor the EIP activities and as a basis for policies. Specifically, the RMS reports on 24 indicators which are grouped in five main subject areas, namely "Raw materials in the global context", "Competitiveness and innovation", "Framework conditions for mining", "Circular economy and recycling", and "Environmental and social sustainability". Besides this, the Strategic Implementation Plan (SIP) is crucial for the EIP which has defined seven specific objectives to be achieved by 2020 [12]. These targets include the identification of conditions for a stable supply of primary raw materials in the EU, alternatives to critical raw materials, promotion of pilot actions, and a network of knowledge.

Besides specific initiatives on raw materials, the EU promotes in any sector social protection, fair working conditions, and equal opportunities and rights in the labor market [13]. As it may be difficult to quantify the mentioned social issues and it may be actually challenging to obtain reliable data on those topics, the EU encourages Corporate Social Responsibility (CSR) and the transparency of environmental and social consequences of companies' business [4,14]. In addition, the Global Reporting Initiative (GRI) provides guidance on how to communicate sustainability issues by developing reporting standards and GRI sector specific indicators for the use of companies and governments [15,16].

1.3. Motivation

Mining has been repeatedly associated with a negative image. Feelings of insecurity are often perceived by the local communities because of the risk of environmental degradation [9] and consequences on human health due to exposure to respirable dust and chemicals and toxic and carcinogenic emissions from tailings [17–19], triggered by mining activities in the area. In addition, there is the fear that the industry may have negative consequences on other coexisting sectors in the area, such as nature tourism and reindeer farming in northern Europe [20]. Depending on the region, the protection of indigenous rights may become an important issue to account for, particularly in view of the affection of these populations to land and water resources, which are moreover crucial for their livelihood [21]. On the other side, the presence of a mine and processing site in a region may trigger opportunities related to job creation and the construction of infrastructures, such as schools, hospitals, and roads [22]. Therefore, social impact evaluation in the mining sector has emerged as a relevant issue regarding both positive and negative aspects [23,24]. Finally, a number of challenges are associated with water related risks, which may cause damages both on the environment and the people. These challenges include water balance management, water quality, tailings dam failures, and site rehabilitation [25].

The present work reports on a sustainability hotspots screening performed in the context of the EU Horizon (H) 2020 "Integrated Mineral Technologies for More Sustainable Raw Material Supply" (ITERAMS) project. The focus of this paper is on social and environmental issues related to mining and on how the outcomes of this preliminary screening study can be used in the context of the sustainability assessment of the ITERAMS solution. The project addresses the H2020 topic of "Sustainable selective low impact mining" and has three main objectives [26]:

- Efficient water recycling, through a reduction in water consumption up to more than 90%, improved water quality, efficient water treatment, and recovery of valuable elements from process water.
- Tailings valorization, with the creation of geopolymers to be used as backfill material and tailings cover, or simply sold as products. Furthermore, the rest of the tailings is planned to be deposited as a filter dry cake.
- Minimization of the environmental footprint, by reducing emissions to the environment, freshwater intake, and the risk of dam accidents.

The combined solutions proposed by ITERAMS are planned to be implemented and validated in three sites, the Kevitsa nickel copper mine in Finland, the Neves-Corvo copper zinc mine in Portugal, and an unspecified platinum mine in South Africa.

The identification and quantification of environmental and social pressures in mining have as a firm basis the definition of a multifaceted approach to capture, at first, issues in the sector at a broader level and, secondly, to characterize these topics for the context of the sites under study. The intention of this work is to present how different challenges related to social and environmental impacts of mining activities have been addressed for the preliminary sustainability hotspots identification in the ITERAMS project. The paper shows how the methodologies explored can help to achieve a better understanding of mining issues; indeed, comprehension is the first essential step towards the improvement of mining sustainability and the related achievement of social equity and environmental responsibility, as highly promoted by the SDGs and European policies and initiatives.

2. Materials and Methods

2.1. Qualitative Modelling Approach

A causal loop diagram (CLD) is an established modeling technique to sketch topics, states, influencing variables, and relations between them, in a graphical way, for any given subject, with by intention low formal overhead and boundaries. Drafting a causal loop diagram (CLD) may be useful in the early phase of a project to better define the system under study, hence identifying the main variables and how they influence and trigger each other. Often, CLDs allow a deeper understanding of the system under study, such as the identification of reinforcing variables, positive or negative feedback loops, or also trade-offs, which often may not be evident at first sight even to domain experts. This becomes important when tackling sustainability because environmental and social impacts may be not only complementary and overlapping, but actually contradictory.

The application of CLDs can be found in literature [27–29]. However, they have been rarely used in Life Cycle Sustainability Assessment (LCSA), despite some guidelines and examples [30–32].

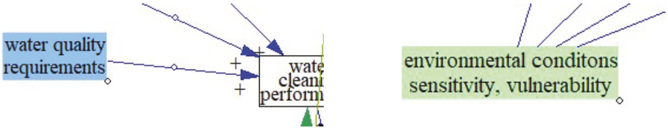
The definition of qualitative cause-effect relationships among the different elements, variables, risks, and impacts of the ITERAMS project was the first operation performed for the hotspots screening, thus resulting in a CLD created in the Vensim software [33]. The intention was to obtain an overview on the issues to be further addressed by the Life Cycle Assessment (LCA) screening and complemented by literature research. Furthermore, attention was focused on those topics which are more difficult to evaluate with LCA, but equally important when interpreting the sustainability hotspots, such as qualitative social aspects and risks. In addition, the CLD shows few reasonings on Life Cycle Costing (LCC) impacts together with social and environmental ones. Although costs are not the focus of this paper, they are reported in the full diagram displayed in Section 3.1 "Results from the Qualitative CLD" not to extrapolate an incomplete picture from the original comprehensive model.

The CLD is referred to mine operation, hence excluding mine installation and closure and exploring the influence of water and tailings treatment technologies on mining.

Specifically, the different elements in the diagram can be described as following:

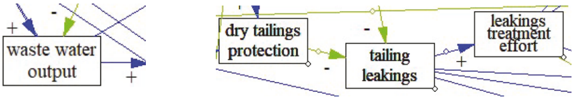
- Variables: external measures and requirements that have an influence on ore mining and processing. This includes, for instance, water quality (see Figure 1a) and security prescriptions, which affect, respectively, the water cleaning effort and the workers' safety.
- External conditions: the mining activity often depends on a number of external situations linked with the area where the site is located, such as hydrological and geological variables, Figure 1b. They may deeply affect the efficiency and the impacts of the operations; on the other side, it might be very difficult to influence the action of those external conditions.
- State boxes: elements of the mining and processing operations, which are influenced by the external variables and conditions, consequently exercising a pressure on the environmental and social dimensions. See Figure 2a.
- Arrows: they are crucial to define the cause-effect relations in the diagram. A blue arrow from "a" to "b" and a "+" sign indicate that "if "a" increases, then "b" increases"; a green arrow from "a" to "b" and a "-" sign indicate that "if "a" increases, then "b" decreases". For instance, Figure 2b shows that if dry tailings protection increases, tailings leaking may be reduced; on the other side, if tailings leaking occurs, the effort spent on leaking treatment increases.
- Inputs: they are elementary and product flows used by processes related to ore mining and processing. These inputs include any energy and consumable, water, and land use, as displayed in Figure 3.
- Risks, occurring in different stages of ore mining and processing, see Figure 4a. They can be reduced by mitigation measures or the implementation of specific new technologies.

- Impacts: pressures on the environment or societal stakeholders, Figure 4b. They can be either positive or negative. They include, for instance, impacts on local communities, workers, ecosystems, and resources.



(**a**) (**b**)

Figure 1. Elements in the causal loop diagram (CLD) for the Integrated Mineral Technologies for More Sustainable Raw Material Supply (ITERAMS) project (**a**) Example of variable: water quality requirement; (**b**) Example of external condition: environmental conditions.



(**a**) (**b**)

Figure 2. Elements in the CLD for the ITERAMS project (**a**) Example of state box: waste water output; (**b**) Example of relations described via arrows: tailings leaking.

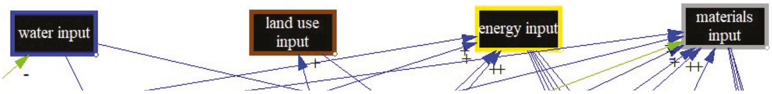
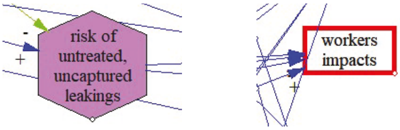


Figure 3. Elements in the CLD for the ITERAMS project. Example of inputs: water, land use, energy, and materials input.



(**a**) (**b**)

Figure 4. Elements in the CLD for the ITERAMS project (**a**) Example of risk: risk of untreated and uncaptured leaking; (**b**) Example of impact: impacts on workers.

The full CLD diagram is displayed in Figure 5 in Section 3.1 "Results from the Qualitative CLD".

2.2. LCA Screening Approach

Beside a qualitative causal loop diagram, the LCA methodology was identified as the main approach to be used for the hotspots screening. LCA is a well-established and internationally recognized technique to assess potential positive and negative impacts occurring across the life cycle of a product or service. Hence, this scientific approach was applied both to the environmental (ELCA) and social (SLCA) dimensions. The already mentioned CLD was a crucial input to the LCA screening, further complemented with literature research [9,20–25,34,35]. Therefore, it is important to highlight the meaningfulness of an iterative and complementary procedure among different screening approaches, namely CLD, LCA, and literature. In fact, this procedure enables a better interpretation of the outcomes in the specific local context of mining activities.

Mining processes representative for the first target of the ITERAMS solution (sulfide ore mining) were investigated in the different countries where the validation sites are located (Finland, Portugal, and South Africa). The processes were selected from well-accepted and renowned databases and calculated in the openLCA software. EXIOBASE and ecoinvent databases were used for the ELCA screening, while the Product Social Impact Life Cycle Assessment (PSILCA) database was identified for the performance of the SLCA screening. Furthermore, environmental and social impacts were evaluated with a number of Life Cycle Impact Assessment Methods (LCIAM) in order to (1) cover all the impact categories important for the project and (2) investigate whether some burdens are unwittingly shifted from one impact category to another. In addition, the application of different LCIAMs was crucial for the cross-checking and identification of those topics which emerged as common sustainability issues to the LCIAMs considered. Specifically, ILCD 2011 Midpoint+, ReCiPe Midpoint H, CML-IA Baseline, Boulay et al. (2011), and built-in EXIOBASE LCIAM were selected for the ELCA screening, while social impacts were calculated by applying the Social Impacts Weighting Method contained in the PSILCA database.

The following steps were undertaken to conduct the screening (as summarized in Table 1):

- Definition of the processes to be investigated: the first focus was set on copper ore mining. However, when related processes were not available in the databases, the focus was extended to mining of metal ores.
- Definition of the locations to be considered for the chosen processes: Finland, Portugal, and South Africa were set as the main focus of the study as the validation sites for the ITERAMS technologies are located in these three countries. Regarding the ELCA screening performed with EXIOBASE, the “copper ores and concentrates” sector was analyzed for Finland, Portugal, and South Africa. On the other side, in the case of the ELCA screening with ecoinvent, the analysis of copper mining had to be extended to Europe as country-specific processes were not available in the database. Copper mining impacts could not be assessed for South Africa using the ecoinvent database. However, moving beyond the first focus of the study, potential environmental impacts of copper mining in South America were evaluated using ecoinvent, given the intention of applying the ITERAMS combined solutions to that region as well in the future. Regarding the SLCA screening, Finland and Portugal were the only two countries analyzed as the third validation site in South Africa had not been identified at the time of the study. The interpretation of SLCA results, in fact, requires a number of background information, which cannot be collected in absence of a specific site location.
- Performance of the environmental LCA screening. The starting point was the comparison of information contained in the databases and the specific details given by the ITERAMS project proposal, for instance regarding water consumption for copper ore processing. Afterwards, environmental hotspots were detected from the calculation of the impacts derived from the processes in the databases. Finally, this was followed by a reflection on the common and different issues which emerged from the analysis of the same process occurring in diverse geographic regions or countries.
- Performance of the social LCA screening. At first, high and very high social risks were identified considering those directly associated with the mining processes to be analyzed. The identification procedure of high and very high social risks was based on the analysis of the risk levels reported in the PSILCA database for the different social indicators assigned to the metal ores mining sector in Finland and Portugal. Afterwards, potential social impacts were assessed including the upstream chain, hence leading to the definition of the social hotspots. Finally, results obtained from the calculation of mining processes were compared to social impacts generated by an average sector in the country. This latter operation was important to compare sector specific risks and impacts with the general social situation in the country.
- The study was complemented by the definition of complementary and overlapping issues between the environmental and social dimensions. Furthermore, possible trade-offs were investigated as well, as further explained in Section 4.1. Literature research was crucial for the interpretation of

results and the definition of the background situations with an influence on the impacts detected with the LCA study.

Table 1 offers an overview of the processes, locations, databases, and LCIAMs investigated for the LCA screening study.

Table 1. Definition of the locations, databases, Life Cycle Impact Assessment Methods (LCIAMs) and processes considered for the Environmental Life Cycle Assessment (ELCA) and Social Life Cycle Assessment (SLCA) screenings.

Approach	ELCA	SLCA
Geographic area	Finland (FI), Portugal (PT), South Africa (ZA), Europe (RER) and Latin America (RLA)	Finland (FI), Portugal (PT)
Database	Ecoinvent v.3.4, EXIOBASE v.2.2	PSILCA v.2 [1]
LCIAM	ILCD 2011 Midpoint+, ReCiPe Midpoint H, CML-IA Baseline, Boulay et al. (2011), and built-in EXIOBASE LCIAM	PSILCA built-in Social Impacts Weighting Method
Process	Ecoinvent for RER and RLA-> copper mine operation | copper concentrate | ; copper production, primary | copper | . EXIOBASE for FI, PT, and ZA -> copper ores and concentrates	PSILCA for FI and PT -> (Mining of) Metal ores

Note: [1] A cut-off of 1E-5 is applied for the creation of the product systems under study.

2.3. *Definition of the "Background Situations"*

The definition of the context of the mining operations is crucial to interpret the LCA results and, hence, identify the environmental and social hotspots. In particular, it is possible to determine the so-called "background situations" which may have either a positive or negative influence on the so-called "stressors". The stressors are pressures on the environmental and social dimensions that may be either mitigated or intensified by background existing conditions. For instance, the dependence of local communities on local water reserves can be considered as a background situation which may worsen the impact of water withdrawal for ore processing. Indeed, if those local water resources are used by local populations for agricultural practices, industrial water withdrawal has a greater impact than that it would have in an area with a different socio-economic condition. Table 2 shows an overview on the identified stressors and related background situations to be considered for the interpretation of the environmental and social impacts of the ITERAMS solution. Specifically, for the present LCA screening the following criteria were determined, most of them traceable in Table 2:

- Vulnerability of local communities, such as the already mentioned dependence on local water reserves. The human capital may have an influence on the impacts as well, for instance if a consistent share of the population suffers from HIV or respiratory problems, impacts generated by mining operations may worsen the health conditions of those weaker individuals.
- Conflicts with other competing sectors in the area, for instance, in terms of workforce or resource use. Considering the validation sites in Finland and Portugal, the local community in the area of the Portuguese mine lives from agriculture of olives and cork [36], while reindeer farming and nature tourism are two competing sectors in Northern Finland [9,20].
- Availability and status of local water and mineral resources. Information can be usually derived from national environment institutes. As for Finland, it is possible to highlight that the condition of freshwater is generally good, with the exception of coastal water where the ecological status is very poor due to eutrophication [37]. In Portugal, the condition of surface water is classified as "reasonable" in most areas; however, some areas on the coast and inner central southern territories display a poor or very poor condition [38]. It is necessary to clarify that data for Finland and Portugal are referred to 2015 and 2013 respectively.

- Importance of the sector for the national and local economy, considering for instance the contribution of mining in the national GDP or the share of local workers hired at the mine sites. For example, as of December 2015, 52% and 36% of workers in Kevitsa (Finland) are hired, respectively, locally (from Sodankylä) and regionally (from Lapland) [39].
- Risks at a national level, hence not related to the mining sector. They may include public sector corruption and sanitation and drinkable water coverage in the country. Indeed, social and socio-economic national and sector-specific risks can influence each other.
- Stability of risks and impacts over the life cycle, which may be useful to detect the contribution of the supply chain to overall results, hence leading to the identification of direct and indirect risks and impacts of the mining activity in a given area.

Table 2. Definition of stressors and background situations which have an influence on the potential environmental and social risks and impacts.

Category	Stressor	Background Situation
Environmental	Tailings leaking	Tailings composition, soil composition
	Emissions from tailings	Tailings composition
	Geopolymers creation from tailings	Tailings composition
	Chemical products for flotation	Ore to be processed, flotation steps
	Instability of water cycle	Ore to be processed, flotation steps, water recycle
	Pond evaporation	Evaporation rate, local climatic conditions
	Pond seepage	Vicinity of water resources, e.g., groundwater reserves, rivers
	Water contamination from tailings	Vicinity of water resources, tailings composition
	Efficiency of water treatment	Tailings composition, ore beneficiation steps and efficiency, type of reagents
	Energy use for ore processing	Ore to be processed, flotation steps
	Water quality	Water treatment process and related efficiency
	Water pollution	Vicinity of water resources, tailings composition
	Air quality	Emissions from ore beneficiation processes and tailings
Social	Unemployment rate in the country/area	Employment conditions in the area, incentives for industrial activities
	Presence of safety measures at the workplace	Safety risk linked to ore beneficiation and wastewater treatment process
	Air quality	Emissions from ore beneficiation process and tailings, preexisting air quality conditions
	Water pollution	Importance of water resources for local communities
	Industrial water use	Dependence of local communities on local water reserves
	Accident rate at the workplace	Safety risk linked to ore beneficiation and wastewater treatment process
	Water contamination from tailings	Importance of water resources for local communities
	Vicinity of touristic areas to the mine	Tourist presence in the area, presence of cultural heritage and natural sites
	Contribution of the sector to economic development	Importance of the mining sector for the local/national economy, share of the sector in the GDP
	Risk of natural disasters	Preexisting natural local conditions (e.g., high risk of earthquakes), type of industrial activities in the area
	Access to material resources	Availability of ores and other resources in the area, e.g., water
	Presence of indigenous population	Share of indigenous population in the area, inclusion of indigenous people in the local society and economy, presence of negotiated agreements for indigenous water rights
	Fair salary	Labor cost, minimum and living wage, workers' wage
	Working time	National regulation on working time, number and duration of shifts per day
	Legal issues	Type of working contracts, national regulation on working contracts
	Workers' rights	Local situation regarding the respect of workers' rights and freedom of association
	Child/forced labor	National/local regulation on the topic, share of child/forced labor in the country/area/sector
	Healthy living conditions	Pollution level of the country/area and sources of the pollution
	Migration	Share of migrant workers in the sector, social inclusion policies
	End of life responsibility	Local/national regulations promoting recycling, reuse, and responsible disposal

3. Results

3.1. Results from the Qualitative CLD

The CLD explores risks and impacts generated by the different processes of the mine operation, see Figure 5 for a complete picture. The focus is the investigation of the different variables and resource inputs which affect the water cycle at the mine site. Furthermore, attention is paid to the issue of tailings disposal and on how this may be influenced by diverse hydrological conditions and water recycling approaches. Specifically, risks derived from process operation, untreated and uncaptured leaking, and dam accidents are highlighted in the diagram in Figure 5.

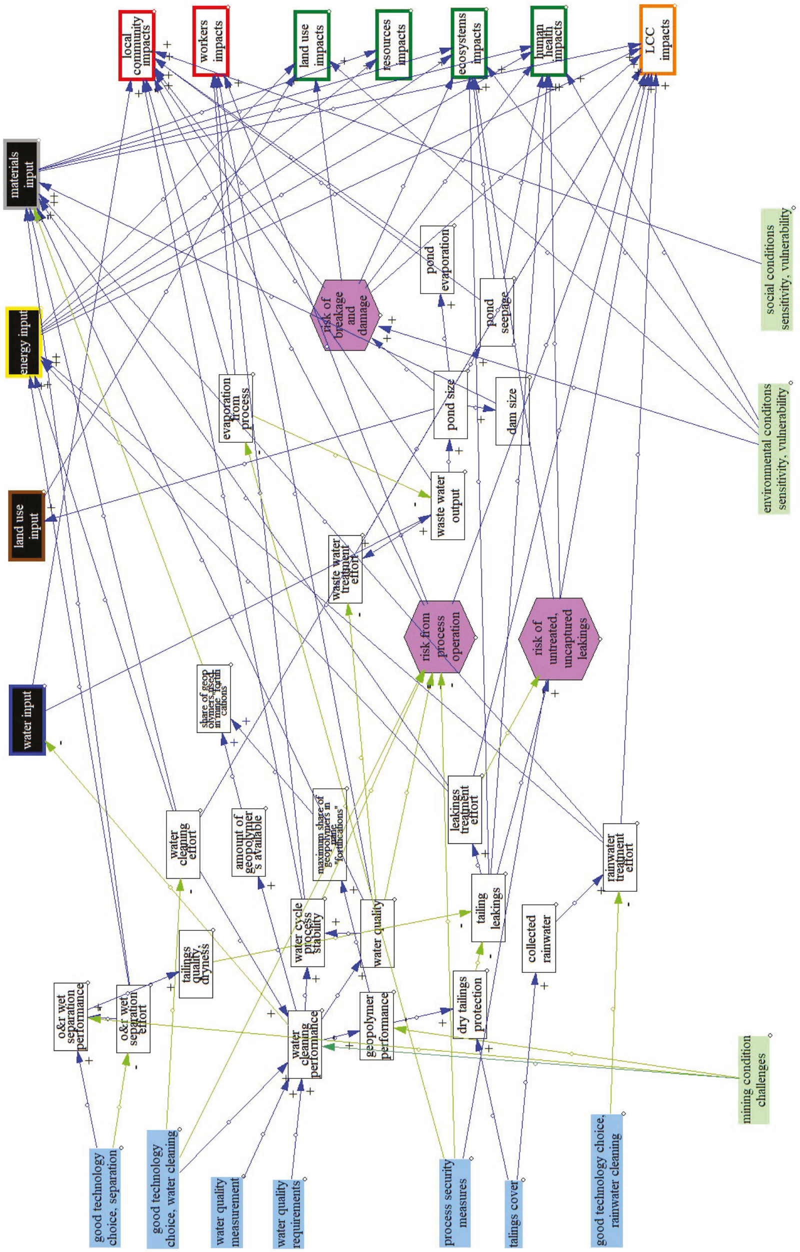


Figure 5. Complete view of the causal loop diagram representing the operation of the mine. LCC: Life Cycle Costing.

The CLD displays the influence of risks and technology choices on social and environmental impacts with reference to consequences on workers and local communities for the social side and on ecosystems, resources, land use, and human health for the environmental dimension. However, the human health issue can be related directly to the social sphere, hence stressing the complementarity between the two dimensions.

Figure 6 explains the relations among the different elements in the diagram which affect human health impacts; brackets indicate that the element has already appeared in the diagram, in this case in Figure 6. Therefore, in this example, it is possible to detect the impact contribution of energy and material inputs for water cleaning and tailings treatment effort. Furthermore, a number of risks related to tailings leaking and dam accidents can exacerbate the potential consequences on human health. Finally, environmental conditions together with tailings deposit characteristics, such as the pond size, may have an additional role in the proportion by which tailings treatment affects health conditions of workers and local populations.

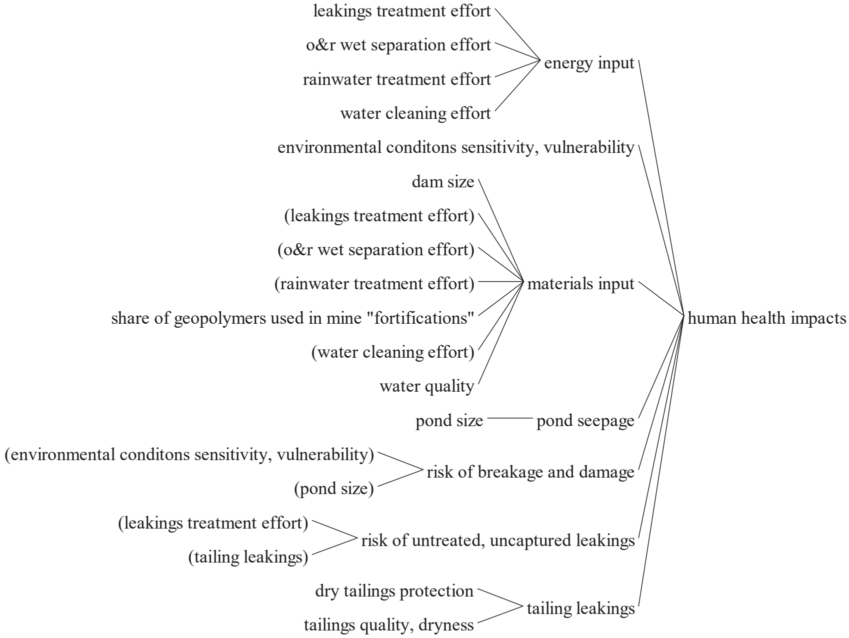


Figure 6. Tree causality diagram: impacts on human health.

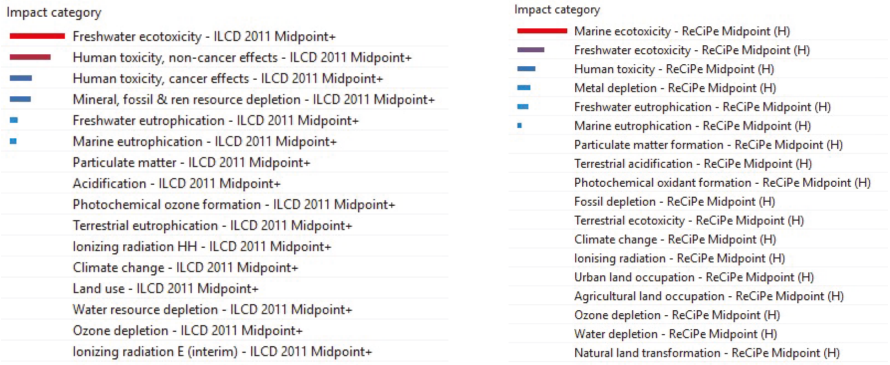
In addition, the CLD investigates the relations around the geopolymers creation which is a crucial point for the ITERAMS project. For instance, a good geopolymers performance may positively influence dry tailings protection, hence preventing tailings leaking and evaporation with a consequent reduction of impacts on human health and ecosystems.

3.2. Results from the Environmental LCA Screening

The ELCA screening reports results calculated with different databases and methods pursuing, this way, the method of triangulation. The processes analyzed with ecoinvent, namely "copper mine operation" and "copper production, primary", include a number of life cycle stages, such as copper mining in ground, blasting, grinding, flotation, concentration, and tailings disposal. Furthermore, the processes account for consumables and energy used during ore extraction and beneficiation, for instance chemicals, electricity, and fuel.

Toxicity categories emerged as crucial if the processes in ecoinvent are calculated with the different methods considered, see Figure 7a,b. These toxicity categories include both water related ones, such as freshwater and marine ecotoxicity, and human toxicity, additionally subdivided by the International Reference Life Cycle Data System (ILCD) method by cancer and non-cancer effects. The results presented below are normalized according to the following normalization sets:

- ILCD 2011 Midpoint+: EU27 2010 normalization.
- ReCiPe midpoint H: World ReCiPe H normalization. The most recent ReCiPe method (2016) could not be used as normalization is not foreseen.
- CML-IA baseline: EU 25 normalization.



Impact category
Freshwater ecotoxicity - ILCD 2011 Midpoint+
Human toxicity, non-cancer effects - ILCD 2011 Midpoint+
Human toxicity, cancer effects - ILCD 2011 Midpoint+
Mineral, fossil & ren resource depletion - ILCD 2011 Midpoint+
Freshwater eutrophication - ILCD 2011 Midpoint+
Marine eutrophication - ILCD 2011 Midpoint+
Particulate matter - ILCD 2011 Midpoint+
Acidification - ILCD 2011 Midpoint+
Photochemical ozone formation - ILCD 2011 Midpoint+
Terrestrial eutrophication - ILCD 2011 Midpoint+
Ionizing radiation HH - ILCD 2011 Midpoint+
Climate change - ILCD 2011 Midpoint+
Land use - ILCD 2011 Midpoint+
Water resource depletion - ILCD 2011 Midpoint+
Ozone depletion - ILCD 2011 Midpoint+
Ionizing radiation E (interim) - ILCD 2011 Midpoint+

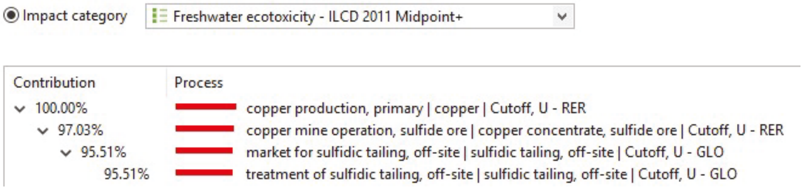
(**a**)

Impact category
Marine ecotoxicity - ReCiPe Midpoint (H)
Freshwater ecotoxicity - ReCiPe Midpoint (H)
Human toxicity - ReCiPe Midpoint (H)
Metal depletion - ReCiPe Midpoint (H)
Freshwater eutrophication - ReCiPe Midpoint (H)
Marine eutrophication - ReCiPe Midpoint (H)
Particulate matter formation - ReCiPe Midpoint (H)
Terrestrial acidification - ReCiPe Midpoint (H)
Photochemical oxidant formation - ReCiPe Midpoint (H)
Fossil depletion - ReCiPe Midpoint (H)
Terrestrial ecotoxicity - ReCiPe Midpoint (H)
Climate change - ReCiPe Midpoint (H)
Ionising radiation - ReCiPe Midpoint (H)
Urban land occupation - ReCiPe Midpoint (H)
Agricultural land occupation - ReCiPe Midpoint (H)
Ozone depletion - ReCiPe Midpoint (H)
Water depletion - ReCiPe Midpoint (H)
Natural land transformation - ReCiPe Midpoint (H)

(**b**)

Figure 7. Copper production, primary | copper | RER, from ecoinvent (**a**) Normalized results, ILCD 2011 Midpoint+ (screenshot from openLCA 1.7); (**b**) Normalized results, ReCiPe Midpoint H (screenshot from openLCA 1.7).

If the most contributing processes to the previously identified toxicity categories are investigated, the treatment of sulfidic tailings off-site clearly emerges as an environmental hotspot for both the water and human toxicity issues (Figure 8). Therefore, this outcome reinforces the purpose of the ITERAMS project which has tailings valorization and reduction of effluents to the environment as core objectives.



● Impact category: Freshwater ecotoxicity - ILCD 2011 Midpoint+

Contribution	Process
100.00%	copper production, primary | copper | Cutoff, U - RER
97.03%	copper mine operation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - RER
95.51%	market for sulfidic tailing, off-site | sulfidic tailing, off-site | Cutoff, U - GLO
95.51%	treatment of sulfidic tailing, off-site | sulfidic tailing, off-site | Cutoff, U - GLO

Figure 8. Copper production, primary | copper | RER, from ecoinvent. Process contribution (including the supply chain) to the impact category "Freshwater ecotoxicity", calculated with ILCD 2011 Midpoint+ (screenshot from openLCA 1.7).

Climate change has not emerged as a major issue from the normalized results presented. However, literature [6] and primary data from mining companies report that the stages of crushing and grinding require a consistent amount of electricity which is, hence, responsible for an important share of GHG emissions during operation. Considering the processes in ecoinvent and the different LCIAMs, the analysis of the most contributing processes to the climate change impact category confirms electricity and blasting as the main environmental hotspots. However, input values for electricity in the analyzed processes in ecoinvent appear to be underestimated if compared to primary data and secondary sources. In addition, the electricity reported by ecoinvent for the investigated mining processes is produced by hydro power; this may be considered as one reason for lower climate change values than expected.

Blue water withdrawal and consumption indicators were analyzed in EXIOBASE for the sector "Copper ores and concentrates" in different countries. Blue water is defined as the "water that has been sourced from surface or groundwater resources and is either evaporated, incorporated into a product or taken from one body of water and returned to another, or returned at a different time" [40]. Figure 9 displays results for Finland, showing that plastic, chemicals, and blending components have a major effect on blue water consumption and withdrawal for manufacturing. If total blue water withdrawal is analyzed, electricity production can be determined as an environmental hotspot, due to cooling operations. Please note that blue water consumption does not include water used for cooling processes, which is hence assumed to be released with a similar quality as the withdrawal.

Name	Category
Water Withdrawal Blue - Total	
P Electricity by gas - RU	EXIOBASE / Russian Federation
P Electricity by nuclear - RU	EXIOBASE / Russian Federation
P Electricity by petroleum and other oil derivatives - EE	EXIOBASE / Estonia
P Electricity by biomass and waste - FI	EXIOBASE / Finland
P Plastics, basic - FI	EXIOBASE / Finland
P Paper and paper products - FI	EXIOBASE / Finland
Water Withdrawal Blue - Manufacturing	
P Plastics, basic - FI	EXIOBASE / Finland
P Paper and paper products - FI	EXIOBASE / Finland
P Chemicals nec - FI	EXIOBASE / Finland
P P- and other fertiliser - FI	EXIOBASE / Finland
Water Consumption Blue - Manufacturing	
P Plastics, basic - FI	EXIOBASE / Finland
P Paper and paper products - FI	EXIOBASE / Finland
P Chemicals nec - FI	EXIOBASE / Finland
P P- and other fertiliser - FI	EXIOBASE / Finland

Figure 9. Copper ores and concentrates, Finland, from EXIOBASE. Process contribution (direct, without upstream chain) to the impact categories "Water Withdrawal Blue—Total", "Water Withdrawal Blue—Manufacturing", and "Water Consumption Blue—Manufacturing", calculated with EXIOBASE built-in LCIAMs (screenshot from openLCA 1.7).

If the same sector is investigated for South Africa and Portugal, it is interesting to compare the value of water withdrawal and consumption and the related hotspots between the three countries, see Table 3. Results include the upstream chain and display that water withdrawal in Finland is notably higher than in South Africa and Portugal. Furthermore, the results show that impacts are more widespread in the life cycle in comparison to the outcomes obtained from the calculation of the processes in ecoinvent with the different impact assessment methods.

Table 3. Main drivers for blue water withdrawal and consumption in Finland, South Africa, and Portugal for the sector "Copper ores and concentrates". Results are calculated for 1 EUR output.

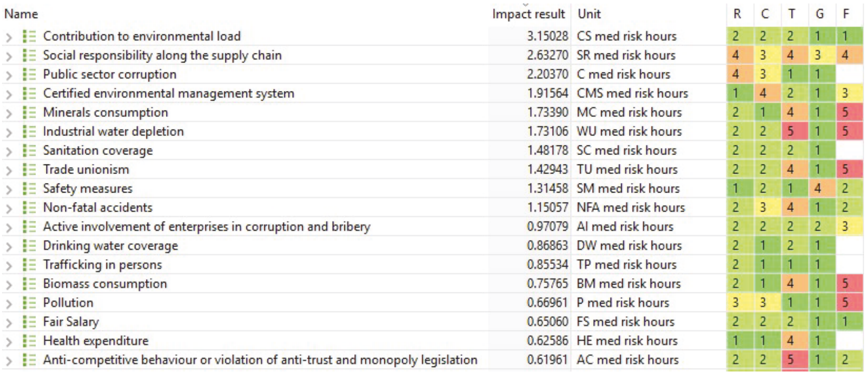
Country	**Blue Water Withdrawal**		**Blue Water Consumption**	
	m^3	**Top 3 drivers**	**m^3**	**Top 3 drivers**
Finland	0.01266	Electricity (gas), RU; Basic plastics, FI; Other business services, FI	0.00554	Additives, BR; Other business services, FI; Basic plastics, FI
	m^3	**Top 3 drivers**	**m^3**	**Top 3 drivers**
South Africa	0.00551	Electricity (coal), ZA; Construction, ZA; Metal products, ZA	0.00516	Electricity (coal), ZA; Supporting transport, ZA; Construction, ZA
Portugal	0.00876	Electricity (gas), PT; Electricity (petroleum and oil derivatives), PT; Distribution and trade services of electricity, PT	0.00223	Hotel and restaurant services, PT; Electricity (gas), PT; heavy fuel oil, PT

3.3. Results from the Social LCA Screening

The SLCA screening enabled, at first, the identification of those high and very high social risks directly linked to mining of metal ores in Finland and Portugal. Both countries present a very high risk of mining companies' involvement in corruption and bribery and of a not socially responsible behavior in the supply chain. Furthermore, a high (in Finland) and very high (in Portugal) risk of non-fatal accidents can be highlighted, with an additional very high risk of fatal accidents in Finland. Industrial water use emerged as an important issue for the Finnish sector, while women discrimination in the labor force and neglect of trade unionism rights could be considered as social issues in the Portuguese industry. The full documentation and explanation of social risks and impact categories in the database are available in the PSILCA manual [41].

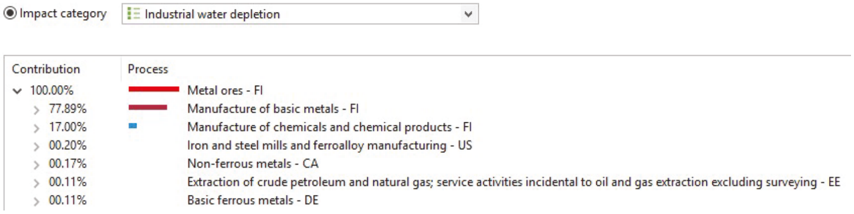
The calculation of potential social impacts related to mining of metal ores in Finland highlights that a number of potential social impacts are not related to the sector as such, but they occur in the upstream chain. Thus, the life cycle under study (Figure 10) displays the highest contribution to sector-specific social themes, such as "Social responsibility along the supply chain", "Non-fatal accidents", "Certified environmental management systems", "Trade unionism", and "Safety measures". However, the last three social topics could not be identified with the previous investigation of high and very high social risks directly linked to the mining process, meaning that those social impacts are largely related to processes part of the supply chain. Results are expressed in medium risk hours and referred to 1 USD output.

Considering that a high risk of water withdrawn for industrial purposes in Finland emerged from the previous process risk analysis, the process contribution to the related social issue was investigated. Furthermore, this social theme was seen crucial for the evaluation of the sustainability of the ITERAMS solution, as additionally confirmed by the CLD and the ELCA screening. Figure 11 displays that most impacts are linked to the upstream processes of basic metals and chemicals manufacturing, with a negligible contribution derived from metal ore mining itself.



Name	Impact result	Unit	R	C	T	G	F
Contribution to environmental load	3.15028	CS med risk hours	2	2	2	1	1
Social responsibility along the supply chain	2.63270	SR med risk hours	4	3	4	3	4
Public sector corruption	2.20370	C med risk hours	4	3	1	1	
Certified environmental management system	1.91564	CMS med risk hours	1	4	2	1	3
Minerals consumption	1.73390	MC med risk hours	2	1	4	1	5
Industrial water depletion	1.73106	WU med risk hours	2	2	5	1	5
Sanitation coverage	1.48178	SC med risk hours	2	2	2	1	
Trade unionism	1.42943	TU med risk hours	2	2	4	1	5
Safety measures	1.31458	SM med risk hours	1	2	1	4	2
Non-fatal accidents	1.15057	NFA med risk hours	2	3	4	1	2
Active involvement of enterprises in corruption and bribery	0.97079	AI med risk hours	2	2	2	2	3
Drinking water coverage	0.86863	DW med risk hours	2	1	2	1	
Trafficking in persons	0.85534	TP med risk hours	2	1	1	1	
Biomass consumption	0.75765	BM med risk hours	2	1	4	1	5
Pollution	0.66961	P med risk hours	3	3	1	1	5
Fair Salary	0.65060	FS med risk hours	2	2	2	1	1
Health expenditure	0.62586	HE med risk hours	1	1	4	1	
Anti-competitive behaviour or violation of anti-trust and monopoly legislation	0.61961	AC med risk hours	2	2	5	1	2

Figure 10. (Mining of) metal ores, Finland, from PSILCA. Overall social impacts associated with the life cycle under study, calculated with Social Impacts Weighting Method in PSILCA. The assessment of data quality is included in the results (screenshot from openLCA 1.7).



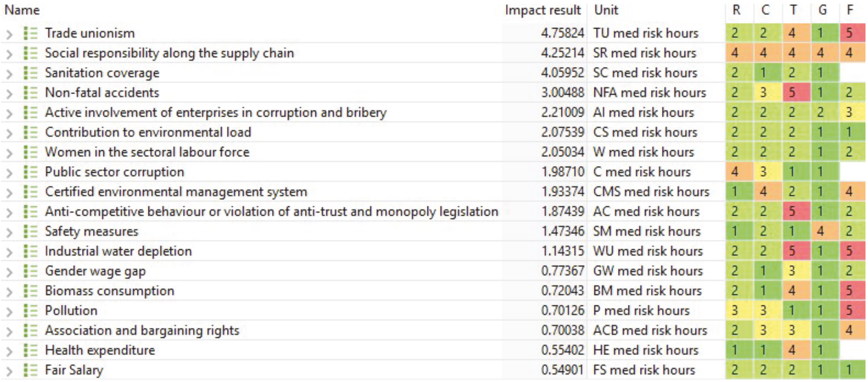
● Impact category: Industrial water depletion

Contribution	Process
100.00%	Metal ores - FI
77.89%	Manufacture of basic metals - FI
17.00%	Manufacture of chemicals and chemical products - FI
00.20%	Iron and steel mills and ferroalloy manufacturing - US
00.17%	Non-ferrous metals - CA
00.11%	Extraction of crude petroleum and natural gas; service activities incidental to oil and gas extraction excluding surveying - EE
00.11%	Basic ferrous metals - DE

Figure 11. (Mining of) metal ores, Finland, from PSILCA. Process contribution (including the supply chain) to the impact category "Industrial water depletion", calculated with Social Impacts Weighting Method in PSILCA (screenshot from openLCA 1.7).

The Portuguese sector of mining of metal ores shows that a number of potential social impacts are associated with the sector, hence with a less contribution derived from processes happening in the upstream chain. This outcome is, therefore, different from the picture outlined for the Finnish mining sector previously analyzed, for which the supply chain emerged as important for most social impact categories. This may be explained, on one side, with the starting risk levels in the upstream processes of the two countries; on the other side, the activity variable (working hours) is more than three times higher for the Portuguese process than for the Finnish one. The activity variable is crucial for the quantification of a social risk and expresses its importance in the product life cycle. In the context of the two countries under study, the Portuguese sector needs 0.01827 working hours to produce 1 USD output of the sector, while only 0.00563 working hours are required in Finland to generate 1 USD output for the metal ores mining sector.

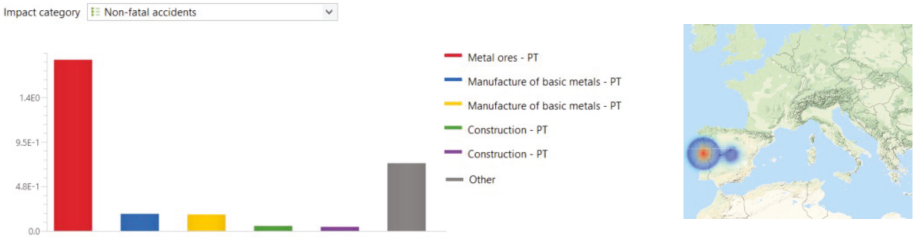
Figure 12 displays the product life cycle contribution to social impacts for 1 USD output. A high amount of medium risk hours can be detected for "Trade unionism", "Social responsibility along the supply chain", "Non-fatal accidents", and "Active involvement of enterprises in corruption and bribery". A minor contribution from upstream processes can be noted for the mentioned sector-specific impact categories. Besides this, social risks at the country level can be highlighted, such as sanitation coverage and public-sector corruption.



Name	Impact result	Unit	R	C	T	G	F
Trade unionism	4.75824	TU med risk hours	2	2	4	1	5
Social responsibility along the supply chain	4.25214	SR med risk hours	4	4	4	4	4
Sanitation coverage	4.05952	SC med risk hours	2	1	2	1	
Non-fatal accidents	3.00488	NFA med risk hours	2	3	5	1	2
Active involvement of enterprises in corruption and bribery	2.21009	AI med risk hours	2	2	2	2	3
Contribution to environmental load	2.07539	CS med risk hours	2	2	2	1	1
Women in the sectoral labour force	2.05034	W med risk hours	2	2	2	1	2
Public sector corruption	1.98710	C med risk hours	4	3	1	1	
Certified environmental management system	1.93374	CMS med risk hours	1	4	2	1	4
Anti-competitive behaviour or violation of anti-trust and monopoly legislation	1.87439	AC med risk hours	2	2	5	1	2
Safety measures	1.47346	SM med risk hours	1	2	1	4	2
Industrial water depletion	1.14315	WU med risk hours	2	2	5	1	5
Gender wage gap	0.77367	GW med risk hours	2	1	3	1	2
Biomass consumption	0.72043	BM med risk hours	2	1	4	1	5
Pollution	0.70126	P med risk hours	3	3	1	1	5
Association and bargaining rights	0.70038	ACB med risk hours	2	3	3	1	4
Health expenditure	0.55402	HE med risk hours	1	1	4	1	
Fair Salary	0.54901	FS med risk hours	2	2	2	1	1

Figure 12. (Mining of) metal ores, Portugal, from PSILCA. Overall social impacts associated with the life cycle under study, calculated with Social Impacts Weighting Method in PSILCA. The assessment of data quality is included in the results (screenshot from openLCA 1.7).

The geographic localization of social impacts related to metal ores mining in Portugal is less widespread for a number of impact categories if compared to Finland. Figure 13a displays the direct process contribution, without upstream chain, to "Non-fatal accidents". The highest share of the impacts is due exactly to the Portuguese mining sector as such. Basic metals manufacturing and the construction sector in Portugal can be identified as other social hotspots (both from commodities and industry fields). Furthermore, in this case, impacts can be localized in Portugal and, to a small extent, in Spain, Figure 13b.



(**a**) (**b**)

Figure 13. (Mining of) metal ores, Portugal, from PSILCA, calculated with Social Impacts Weighting Method in PSILCA (**a**) Process contribution (direct, without upstream chain) to the impact category "Non-fatal accidents"; (**b**) Geographic localization of the impact category "Non-fatal accidents" (screenshots from openLCA 1.7).

4. Discussion

4.1. Identification and Interpretation of the Sustainability Hotspots

The CLD provided a number of useful inputs to be further developed with both the LCA screening and the literature research. Several cause-effect relations in the diagram confirmed what was expected, for instance in terms of dam accidents which may be reduced or even eliminated with the ITERAMS implementation. Indeed, the risk of dam breakage and damage increases with the dam size which, in turn, generates a higher land use. Therefore, less wastewater output due to a more efficient water recycling and the production of dry tailings are supposed to decrease risks and impacts on ecosystems, human health, workers, and local communities. On the other side, the CLD shows less straightforward relations among the different items, leading to the identification of a number of trade-offs. The closed loop water cycle planned by ITERAMS, for instance, may lead to a more efficient water recycling, but concurrently to higher impacts on human health due to the higher energy required and produced to isolate the water cycle in the different ore beneficiation steps, Figure 14.

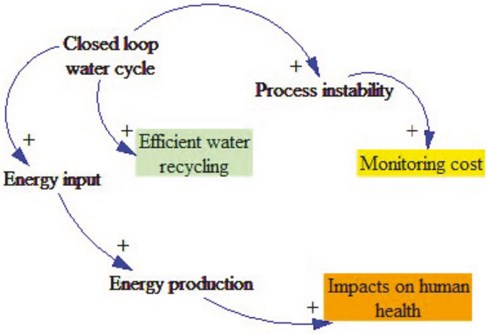
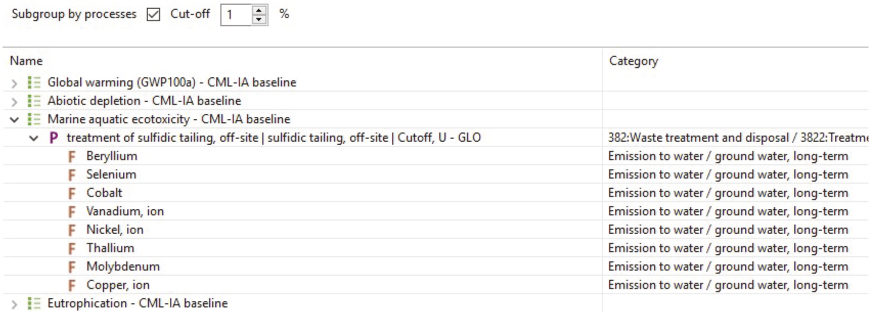


Figure 14. Example of trade-off investigation with a CLD (screenshot from Vensim).

The ELCA screening highlighted tailings treatment as the main environmental hotspot. In particular, tailings disposal may cause serious damages both to the environment and human health due to heavy metals toxic emissions which pollute air and water resources. Figure 15, for example, shows the most contributing flows to the impacts generated by the treatment of sulfidic tailings in the context of marine aquatic ecotoxicity.



Subgroup by processes ☑ Cut-off 1 %

Name	Category
Global warming (GWP100a) - CML-IA baseline	
Abiotic depletion - CML-IA baseline	
Marine aquatic ecotoxicity - CML-IA baseline	
P treatment of sulfidic tailing, off-site | sulfidic tailing, off-site | Cutoff, U - GLO	382:Waste treatment and disposal / 3822:Treatm
F Beryllium	Emission to water / ground water, long-term
F Selenium	Emission to water / ground water, long-term
F Cobalt	Emission to water / ground water, long-term
F Vanadium, ion	Emission to water / ground water, long-term
F Nickel, ion	Emission to water / ground water, long-term
F Thallium	Emission to water / ground water, long-term
F Molybdenum	Emission to water / ground water, long-term
F Copper, ion	Emission to water / ground water, long-term
Eutrophication - CML-IA baseline	

Figure 15. Copper mine operation | copper concentrate | RER, from ecoinvent. Flow and process contribution to the impact category "Marine aquatic ecotoxicity", calculated with CML-IA baseline method (screenshot from openLCA 1.7).

Furthermore, although a number of differences in results can be noticed between different geographic locations, environmental impacts are not excessively globally widespread, meaning that they are usually confined to the geographic region or continent. On the other hand, a different outcome may be highlighted for the SLCA screening where the supply chain and geographic impact distribution emerged as crucial for a number of social issues or even countries.

An interesting insight on social impacts is offered by the comparison between the mining sector and an average industry in the country. If this operation is performed for Finland (Figure 16), social impacts of metal ores mining result higher than those of an average Finnish sector, especially regarding "Contribution to environmental load", "Social responsibility along the supply chain", "Industrial water depletion", and "Safety measures".

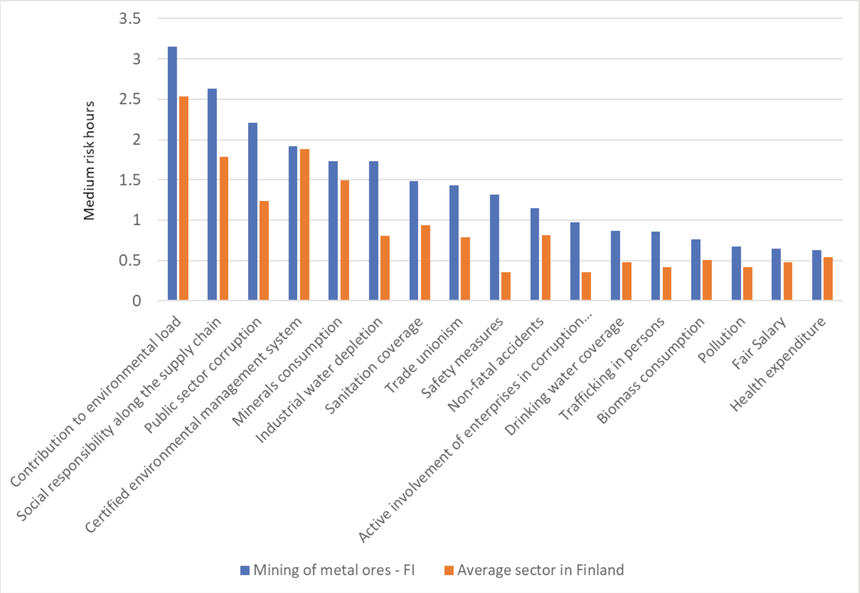


Figure 16. Comparison of social impacts between "(Mining of) metal ores, Finland" and an average Finnish sector. Calculation with Social Impacts Weighting Method in PSILCA, results referred to 1 USD output.

The main social hotspots related to a number of impact categories for mining of metal ores in Finland are basic metals and chemicals manufacturing in Finland, construction in China and India, and machinery production in Russia. This outcome stresses the high contribution of the processing stages, such as flotation, to overall impacts. Furthermore, several impacts occurring in the supply chain can be localized in Asian countries. In the case of the analyzed Portuguese mining sector, basic metals manufacturing in Portugal, metal products in China and Angola, and motor vehicles and engines manufacturing in USA can be regarded as social hotspots. Besides, construction in India and China together with the direct impacts linked to the mining sector itself show an important contribution to the product life cycle in Portugal. As for the Portuguese case, the impacts related to the mine and processing plant installation appear to be rather consistent.

The interpretation of the identified environmental and social sustainability hotspots can be further developed if the overlapping and complementarity between the two dimensions is further discussed. Indeed, a number of indicators or impact categories may cover the same issue; however, they often express different consequences as they investigate impacts on different stakeholders and characters. Figure 17 shows an example of how water resource depletion due to industrial water withdrawal and consumption for the mining activities may have consequences on the environment, leading to the destruction of material resources and environmental degradation. In parallel, the scarcity or exhaustion of water resources may destroy those local economies which need water for their operations. In both cases, local communities may be highly affected incurring in poverty and resettlement if they are dependent on local water reserves for their livelihood, and hence, easily vulnerable. A second demonstration of this complementarity is provided by tailings leaking which may lead to soil and, consequently, groundwater contamination with severe health problems for the local population, but also with ecosystem impairment.

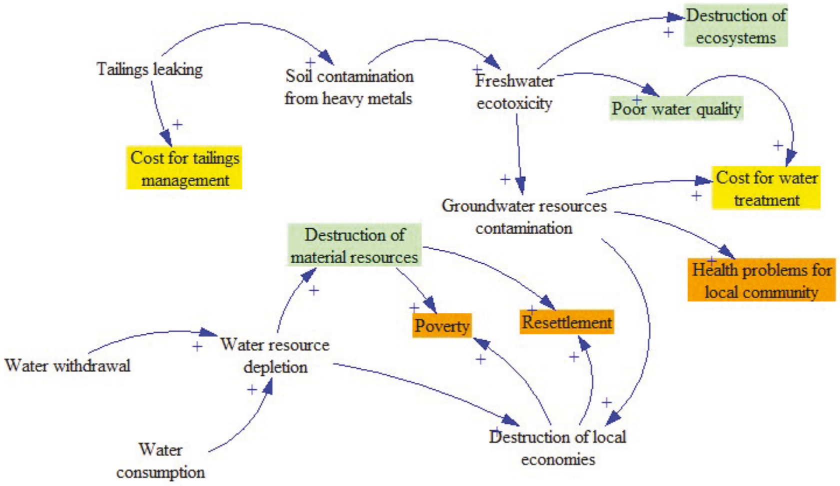


Figure 17. Complementarity and overlapping between the different sustainability dimensions investigated with a CLD (screenshot from Vensim).

4.2. Strength and Weakness of the Study

The different approaches presented in the article jointly led to the identification of the environmental and social hotspots associated with the mining industry and further developed in the context of the objectives of the ITERAMS project. Such an achievement was made possible by the mutual iteration between the CLD, LCA, and literature which from time to time triggered new challenges and reflections.

A number of limitations could be identified with reference to the use of existing databases for the LCA screening. Indeed, it should be considered that databases use statistical data to build some of the information they present; hence, uncertainties related to data gaps, quality, and assumptions may be present [42]. Furthermore, a specific reflection on the uncertainty derived from multi regional input output (IO) models should be made, considering the use of IO databases (EXIOBASE, PSILCA) for the study [43].

Regarding the LCA screening, results are taken directly from the selected databases without altering any input and output value. In this regard, the water and electricity requirements for copper ore mining and processing in ecoinvent are estimated to be rather low in contrast to primary data that will, in turn, be used for the next LCA assessment of ITERAMS. In addition, there is some criticism on the characterization models used to estimate toxicity from heavy metals [44].

Finally, the documentation of the data quality is crucial for the interpretation of results. Data quality is assessed in openLCA using the Pedigree matrix [41,45], further adapted for SLCA. In this latter case, for instance, it should be noted that information for "Trade unionism" and "Non-fatal accidents" is older than five years and that incomplete data are available for "Social responsibility along the supply chain" and "Certified environmental management systems". Few indicators, such as "Trade unionism", "Pollution", and "Industrial water depletion", present a low data quality for the criteria "Further technical conformance". This is due to the fact that data for these indicators are interpolated from the country average as sector-specific information is not available.

5. Conclusions

The sustainability hotspots screening study provided a valuable input to the ITERAMS project. Indeed, it enabled a better understanding of the environmental and social issues associated with mining which are crucial for the creation and evaluation of the specific life cycle model of the

ITERAMS combined solutions. In fact, this work was the first step towards the prioritization of the efforts and resources for the sustainability evaluation of the project. In addition, it provided an important overview to be accounted for when drafting the goal and scope of the following LCA study. Furthermore, this article highlighted the significance of exploring different methodologies and approaches in sustainability assessment. Indeed, once results are calculated, they need to be placed in the context of the mining activities, hence evaluating those specific local and national background situations which influence environmental and social pressures. The study on how the environmental and social dimensions interact with each other was equally fundamental, displaying how often environmental risks and impacts end up on risks and impacts on societal stakeholders. Furthermore, it is worth mentioning that the sustainability screening approach developed in the context of the ITERAMS project can be applied to both other mining case studies and, more broadly, to other different situations if the general reflections and insights given on the methodology, tools, and identification of the background situations are considered.

As a final point, the present study was important for the project as it helped to create a dialogue among the different project partners. The technical partners and the mining companies had, this way, the chance to understand the sense and the approach of LCA and sustainability assessment in general. These understanding and appraisal are crucial for the partners´ commitment and participation to the next stages of the work, starting from the primary data collection at the different mine sites.

Supplementary Materials: The following are available online at http://www.mdpi.com/2079-9276/7/4/80/s1. Figure S1: Tree causality diagram: ecosystem impacts, Figure S2: Tree causality diagram: resources impacts, Figure S3: Tree causality diagram: land use impacts, Figure S4: Tree causality diagram: workers impacts, Figure S5: Tree causality diagram: local community impacts.

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resources

Article

Jumping the Chain: How Downstream Manufacturers Engage with Deep Suppliers of Conflict Minerals

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Abstract: Global manufacturing firms are engaging distant suppliers of critical raw materials to participate in responsible sourcing. Downstream firms are concerned about risks in mineral supply chains of violent conflict, human rights violations, and poor governance, but they are limited in seeing their suppliers. Descriptive data on 323 smelters and refiners of tantalum, tin, tungsten, and gold (the "conflict minerals") were complemented by interviews with downstream firms in the electronics industry. Results provided a narrative of supplier engagement, describing tactics used to identify "deep suppliers" at chokepoints in metals supply and to persuade producers into joining due diligence programs. Top-tier firms collaborate through a standards program to overcame barriers of geography and cultural distance in supply chain management beyond the visible horizon. Curiously, manufacturers do not need line-of-sight transparency to lower-tier suppliers. Rather, top-tier firms are "jumping the chain" to engage directly with "deep suppliers" who may—or may not—be their own actual physical suppliers. The research contributes empirical evidence to understanding multi-tier supply chains, examines how power is exercised by top-tier firms managing suppliers, and provides insights on supply chain transparency. Responsible sourcing, based on due diligence guidance and standards, is becoming expected of companies that are involved in supply chains of raw materials.

Keywords: responsible sourcing; supply chain due diligence; multi-tier supply chains; transparency; sustainable supply chain management; critical raw materials

1. Introduction

Transparency has become a modern expectation of business [1,2]. Big businesses consult with local communities and engage with international non-governmental organizations; firms report on sustainability efforts to investors, to the public, and to other stakeholders. Yet, firms struggle to see past their immediate suppliers, to understand the sources of raw materials, and to know what risks are present multiple tiers into the supply chain [3,4]. Some sectors, like food and pharmaceutical, are more advanced—driven by regulations and imperatives of quality, health, and safety—but in manufacturing sectors, like electronics, automotive, toys, and aerospace, such efforts are just beginning [5,6]. Thousands of suppliers feed raw materials and components into global manufacturing networks to make each product [4]—and modern devices and equipment require a diverse array of rare materials [7]. As such, manufacturers have typically managed only to the "visible horizon", that is they can "see" only a couple tiers into their supply chains [8]. Limited transparency also poses risks of supply disruption, both physical disruption and reputational disruption. Without knowing one's suppliers, there is concern that things will be out of compliance to regulations or fail in quality. More broadly, it limits sustainable supply chain management and the mitigation of environmental impacts and social problems that may be present in distant global supply chains. Recent actions specifically to address "conflict minerals" requirements have begun to reduce this opaqueness in the case of four metals, and have opened opportunities for manufacturers to increase transparency and encourage improvements in social conditions in mining regions by performing "due diligence" [6,9].

This research looks at "responsible sourcing" of minerals and metals: how multinational manufacturing firms manage supply chains to improve supply chain transparency and reduce negative impacts at lower-tier suppliers and in supply chains. Downstream companies are driven by regulation in the United States (U.S.) (and forthcoming in Europe) and by corporate social responsibility (see, for example [10]), supported by evolving market expectations (see, for example [11]). Specifically, this project draws on data from both producer and end-user companies of tantalum, tin, tungsten, and gold (3TG) (Figure 1), which are defined by U.S. regulation as "conflict minerals". Previous research has examined assurance programs and reporting efforts by downstream firms to manage upstream 3TG metal smelters and refiners [5,12,13], and has described characteristics of supplier firms [14].

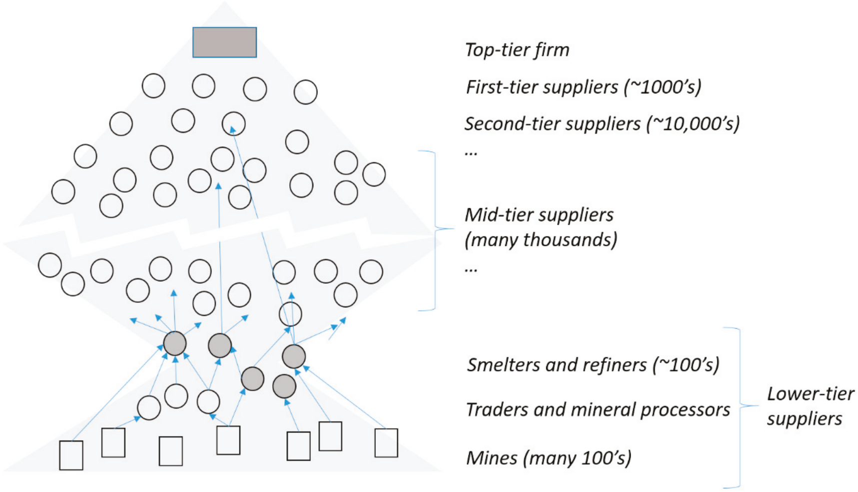

Figure 1. Schematic supply chain of tantalum, tin and tungsten to top-tier firm, showing indicative flows of raw material to and from smelters and refiners. The top-tier firm and smelters and refiners are focal companies in a "diamond shaped" supply chain. Note: the gold supply chain is qualitatively different.

Given the expectations of transparency; given the visible horizon problem in multi-tier supply chains; and, given the importance of critical raw minerals, including several of the conflict minerals, this paper seeks to answer the question: How do global manufacturing firms engage with suppliers in mineral supply chains to enable responsible sourcing? We empirically investigate how top-tier firms have exercised power in multi-tier supply chains to implement sustainable supply chain management and how lower-tier suppliers of minerals and metals have responded to the pressures of sustainable practices.

Raw material supply chains are a relatively new topic for research. Minerals and metals have not been studied to the degree that forestry, food, fisheries, and agriculture have [15,16]. However, responsible sourcing of abiotic resources is emerging rapidly [5,17,18], and this paper makes an empirical contribution in this area. Practically, the analysis presented herein provides insight that may support supply chain management solutions for a larger set of important materials: two of the four conflict minerals (tantalum and tungsten) are commonly characterized as critical raw materials [7,19] that present supply-risk yet are paramount in technologies for a low-carbon economy. Most raw material criticality assessments use data at the national scale [19,20], and few researchers have paid attention to managing real supply chains at the firm-level [20–23], where material choices are made. Looking at how businesses and governments addressed the conflict mineral problem, and develop responsible sourcing, can guide high-level policy and private-sector governance of minerals and raw materials [19,24,25]. Whereas, technical avenues to the critical materials problem, like geological exploration, efficient mining and metallurgy, and materials substitution, are widely touted [7,19], management strategies for mineral governance, like responsible sourcing, are also needed. By better understanding their suppliers, manufacturing firms can "identify and manage critical suppliers" [8] and improve their ability to mitigate sources of supply disruption while maintaining ethical and sustainable sources of raw materials [24].

In this study, data on real firms were used to explore both ends of the mineral supply chain. Upstream, the analysis was on a population of 323 "deep suppliers"—our term for distant lower-tier producers who are positioned at a focal point to mitigate supply chain problems. Here, these firms were smelters and refiners: producers who purchase ore and mineral concentrates from mines and traders, and process these into refined metals and metal chemicals. Downstream, interviews were carried out with six conflict mineral managers in multinational manufacturing firms who are end-users of tantalum, tin, tungsten, and gold. The results showed both expected and novel tactics used by top-tier firms to reach deep suppliers and manage risks in mineral supply. Manufacturers work collaboratively through industry associations to identify, validate, and engage lower-tier suppliers. This includes emails and letter-writing, but also more extreme tactics, such as direct site visits by multi-national firms to small producers in remote regions. Downstream firms also provide financial incentives to deep suppliers to motivate their implementation of due diligence management systems. Surprisingly, it was revealed that manufacturers do not need line-of-sight visibility to lower-tier suppliers in order to manage their practices; rather, top-tier firms are "jumping the chain" to engage directly with deep suppliers who may—or may not—be their own actual physical suppliers.

In the next section, this paper reviews scholarship and practices in mineral supply chains. The Methods section describes the mixed-methods approach and data set, followed by Results, which consider the 3TG supply chains collectively and separately. The Discussion section redresses the research question, considers theoretical contributions, and then discusses practical implications for responsible sourcing of raw materials more generally.

2. Literature Review

This study draws on several fields of research: business scholarship, specifically firm-level operations research in sustainable supply chain management; political science and policy studies, where there is growing interest in private and public sector governance of minerals and metals; sustainability standards, including assurance and certification approaches; and, sustainability science and industrial ecology, specifically on critical raw materials and how firms assess and manage critical raw materials. Together, these perspectives frame how the conflict minerals problem has been managed and the development of due diligence approaches in mineral supply chains.

2.1. Sustainable Supply Chain Management

Building from Hart's classic natural-resource-based view of the firm [1], and recognizing that sustainability actions need to match a company's strategic and financial objectives [2], sustainable supply chain management research has emerged since the early 2000's based on supply chain theory and methods [2,8,26,27]. Most work emphasizes environmental strategies for green products or environmental management of risks of suppliers [27], often overlooking social aspects in supply chains [27,28]. The concept of the "focal company" refers to the top-tier firm in a supply chain who controls design, directs production, and often faces customers directly [27]. Focal firms are frequently brand-name manufacturers with high visibility and reputational status. They thus experience a higher level of scrutiny by stakeholders [1] and they are held to a higher level of responsibility for environmental and social problems [27]. To meet transparency expectations, top-tier firms report on their own sustainability practices, but also look to their suppliers to contribute. Big companies engage and work with suppliers to coordinate supply chains both vertically ("up" and "down" chains) and horizontally across supply networks [2]. General strategies for sustainable supply chain management are assessment and collaboration [29], and more specifically may include communication, education and development, and compliance approaches [28].

In the modern global economy, long complex dynamic supply chains present a "visible horizon" problem [8] for sustainable supply chain management. Large manufacturers may have 1000 first-tier suppliers, 8000 second-tier suppliers, and 30,000 third-tier suppliers [4]. Of interest here are lower-tier suppliers, also referred to as sub-suppliers [30] or extreme upstream suppliers [31], which a top-tier firm is unable to "see" or engage directly. Identifying and engaging lower-tier suppliers is a key difficulty for sustainable supply chain management [30]. Manufacturers are often unaware of who their suppliers are and what are the sources of raw materials used in their own products [32]. Moreover, their power over suppliers diminishes as the distance upstream into the supply chain increases [3]; a manufacturer typically will have direct contractual control only of tier 1 suppliers although may have some influence on suppliers at tier 2. For mineral supply chains, the concern is particularly acute, because some of the greatest negative social and environmental impacts are at or around mines [3], which may be 8 or 10 tiers removed from the end-product [13,33,34] (see Figure 1).

Although there is scant research on managing lower-tier suppliers [30], literature suggests direct and indirect means which top-tier firms can apply [3,29] and research shows that working with strategic partners, like standards programs or third parties, is useful [3,30,31]. Sauer and Seuring proposed a "cascaded approach" to multi-tier sustainable supply chain management specific to mineral supply chains [35]. In the current work, we add to this discussion, based on our empirical examination of supply chains of the four 3TG metal industries. Research looking at the structure and shape of multi-tier supply chains suggests that beyond the visible horizon there will be a tendency for overlap in multi-tier supply chains, creating "diamond-shaped" supply chains that present a sensitivity to disruption risk [36]. In mineral commodity supply chains, such overlapping supply chains are significant: even though a manufacturer may have thousands of fabrication and assembly suppliers at the third-tier [4], there are limited numbers of commodity processors (e.g., makers of metal alloys and chemicals) and raw materials producers (e.g., producers of basic chemicals and refined metals). Consequently, there are chokepoints [5], where material is moving through a limited number of specialized facilities. In some cases, particularly for critical raw materials, there will be fewer than 50 facilities that process the entire global supply of one metal [33]. Sauer and Seuring have considered how in mineral supply chains these companies can act as "upstream focal firms" [37] that have the ability to oversee upstream mineral extraction and processing. Our research looks at chokepoints in 3TG supply chains, and responds to scholars who have considered theoretical factors in multi-tier sustainable supply chain management [3,8,35]. Chokepoints present a constriction in complex global supply chains where there are few actors and fewer sites, thus providing strategic opportunities for efficient engagement, education, development, and standardization.

2.2. Governance of Mineral and Metal Supplies

Governance of minerals and raw materials has emerged as an important concern [24] for both public and private sectors. Society is increasingly relying on greater diversity and varieties of materials to satisfy modern wellbeing, while also transitioning to a low carbon economy [7,19,38]. Europe, the United States, Japan, Korea, and other nations have identified "critical raw materials" that are economically crucial yet that also face supply risks. National agencies have assessed raw material criticality [19,20], and support research on technical solutions, including geological exploration, efficient mining and metallurgy, and materials substitution [7,19]. New trade relationships and strategic material stockpiling are other national strategies that support military needs and important industries.

Traceability of minerals is generally low when compared to biotic commodities. Traceability of food, for example, is necessary if there is a product recall [39]. Or consider wine, which from taste alone can be traced to a location or producer, or bananas that remain intact from farm to table and can be clearly marked. Chemical tests performed at the molecular level are effective at tracing food, fibre, and wood. Even minerals, "geochemical fingerprinting" of structure and trace elements can be used [40]—but only to the smelter where minerals are converted into metal form. Once in metal form, chemical traceability is not feasible.

2.3. Critical Raw Materials Management

Minerals and metals present particular challenges for firms seeking transparency in their supply chains. Tracking and tracing of minerals sources are difficult for business reasons, like the number of actors in supply chains, the complexity of international commerce, including trade of intermediate materials, and business confidentiality; and, for physical reasons, like mixing of mineral ores, mixing of primary materials with recycled sources, chemical transformation of minerals to metals, and physical conversions of form like melting [5,13,33,34]. Given concerns about critical raw materials, and acknowledging it is at the firm-level that material engineering and design decisions are made, firm-level approaches to dealing with critical raw materials are less well studied, including few case studies [23,41], methodological suggestions [20,21], and business strategies [22].

Sustainability standards and certifications are a growing approach used by business to govern supply chains. Suppliers are expected to implement standards of sustainability performance and management systems that have been written by downstream buyers. Conformance of suppliers is assured via third party auditing, and it is often presented as supplier certification. Some sectors, like forestry, food, and pharmaceutical are relatively advanced in this mechanism [16], where health, safety, and quality requirements necessitate vertical coordination along supply chains. In sectors like electronics, automotive, toys, and aerospace, supply chain sustainability standards and programs are just beginning and are relatively understudied, with few exceptions [42]. Certification approaches that are relevant to mineral extraction and metal supply chains are have been reviewed [5,18,25,33]. Efforts on diamond certification involve national authority [42], whereas business-led initiatives are newer. Some industry-specific studies have been done for other minerals and metals, including mention of steel [43], aluminum [5,18], and gems [44], but the most research has been on conflict minerals (see for example [5,13,33]).

2.4. Conflict Minerals

The core problem of conflict minerals is that extraction activities in the eastern Democratic Republic of the Congo (DRC) are financing conflict and associated with forced labor and human rights violations [5,6,13,45,46]. Section 1502 of the United States *Dodd-Frank Wall Street Reform and Consumer Protection Act* (Dodd-Frank Act) defined tantalum, tin, tungsten, and gold as "conflict minerals" in 2010. Starting in 2014, U.S. publicly traded companies were regulated to report to the U.S. Securities and Exchange Commission (SEC) regarding the use of conflict minerals in their products [47]. It is important to clarify that the U.S. regulation concerns only reporting of 3TG sources and due diligence measures: it does not restrict imports or control the use of raw materials. Of course, by reporting publically on sources, U.S. firms are motivated to develop more responsible supply chains. In 2021 the European Union Conflict Minerals Regulation takes effect and also has firm-level reporting requirements [48]. Although not a regulation, there is a parallel guideline published by the China Chamber of Commerce of Metals, Minerals, and Chemicals Importers & Exporters (CCCMC), regarding metal trade for Chinese firms. Importantly, these government efforts mean that all sources and all supply chains of each the four metals are subject to scrutiny, requiring downstream firms to be transparent about the origins of tantalum, tin, tungsten, and gold used in their products. This motivates firms to look far beyond manufacturing activities in the United States or Europe, and beyond a focus on mining in Central Africa.

2.5. Due Diligence

The United States and EU rules, and the Chinese guideline, refer to the Organisation for Economic Cooperation and Development *OECD Due Diligence Guidance for Responsible Supply Chains of Minerals* *from Conflict-Affected and High-Risk Areas* (OECD guidance) [9], which outlines policies, due diligence frameworks, and management systems for mineral supply chain actors. Under the OECD guidance, companies that are involved in mineral supply chains are asked to consider a wide range of concerns that are associated with all stages of mineral resource extraction, metal processing and manufacturing. All actors in mineral supply chains, from miners to end-users, are encouraged to implement the five-steps of due diligence described in the OECD guidance:

- STEP 1: Establish strong company management systems
- STEP 2: Identify and assess risks in the supply chain
- STEP 3: Design and implement a strategy to respond to identified risks
- STEP 4: Carry out independent third-party audit of refiner's due diligence practices
- STEP 5: Report annually on supply chain due diligence

The OECD five-step process compares to the definition for due diligence that is provided by Hofmann, Schleper, and Blome, as an approach of "gathering of internal and external information and gaining a sound knowledge of the company, its industry, financial condition, customers, competitors, suppliers, business processes, technology and, above all, management; [and] sharing relevant upstream information with downstream partners" [6].

The OECD guidance uses the term "conflict-affected and high-risk areas" (CAHRA) to refer to regions where there is probability of serious physical harm to people, including violent conflict, sexual violence, and non-state armed groups, but also includes concerns, such as forced labor, child labor, torture, and financial crimes such as money laundering. CAHRA are assessed at national and sometimes subnational levels using various indicators of conflict, poor governance, and human rights violations. The OECD guidance acknowledges the importance of the chokepoint at smelters and refiners, which OECD refers to as the "control point" in mineral supply chains. The due diligence approach encourages firms to monitor material flows [45], and collaborate to provide supply chain transparency [6]. The OECD guidance has led to numerous business-led programs and standards that support due diligence and responsible sourcing in mineral supply chains.

3. Data and Methods

A parallel convergent mixed method was used, where both descriptive variables and qualitative interview data were analyzed separately, and then integrated. Descriptive data were provided by the Responsible Minerals Initiative, a global industry association based in the U.S. that runs a due diligence program on mineral supply chains. The program provided details on the 323 known smelters and refiners of tantalum, tin, tungsten, and gold (Table 1). Data on upstream suppliers were complemented by interviews with downstream manufacturing firms. Semi-structured interviews were completed with six current and former members of the program's smelter engagement team. Together, these approaches allowed us to produce a narrative of engagement, including nuances for each of the four 3TG metal industries, detailing external forces and tactics used by the initiative, and describing how downstream manufacturing firms identified and communicated with upstream metal producers.

The domain of conflict minerals provides a valuable and a rich source of data for applied research on responsible sourcing. Activity in due diligence is particularly advanced in 3TG supply chains, as compared to other metals and to other commodities. Data are available as far back as 2008 on supply chains, standards, and downstream firms concerned about conflict minerals.

The three main due diligence programs, which cross-recognize each other's listings, operate for the benefit of downstream metal users: (1) the Responsible Minerals Initiative, which is described below; (2) the Responsible Jewellery Council, which has more than on thousand member companies from miners to manufacturers to retailers; and, (3) the London Bullion Market Association, whose members includes over one-hundred miners, refiners and other actors in the global market for precious metals. Smaller regional programs on conflict-free gold are operated at the Dubai Multi Commodities Center and the Shanghai Gold Exchange.

Table 1. Population and due diligence status of known tantalum, tin, tungsten, and gold (3TG) smelters and refineries (as of late 2017).

	Tantalum	Tin	Tungsten	Gold[1]	TOTAL
Known facilities, worldwide	44	83	46	150	**323**
Facilities in China	18	17	28	24	**87**
Facilities participating in due diligence programs	44	78	44	114	**280**
Percent participating	100%	94%	96%	76%	**87%**
Facilities conformant to due diligence standards	39	73	40	101	**253**
Percent conformant	89%	88%	87%	67%	**78%**

[1] For gold the population is limited to industrial size gold refiners.

The 323 suppliers that are considered in the current study constitute the population of 3TG smelters and refiners (as of late 2017) known to the three main due diligence programs. Notably, the significant majority of suppliers are conformant to due diligence standards (Figure 2). For tantalum, tin, and tungsten, more than 80% of suppliers are participating in due diligence programs. For gold the number is lower, with about 75% conformant. For gold, it should be noted that this value is the fraction of known of industrial gold refiners (i.e., those producing greater than about 1 tonne per year); however, many hundreds of small and very small (e.g., less than one kilogram per year) refineries are known, but are assumed not to supply industrial manufacturing networks. Note also, for all four metal industries, there is an observable variation in the population, as firms go out of business or new firms emerge. There is also the possibility that the programs have not identified and confirmed all operating facilities, most notably black-market operators.

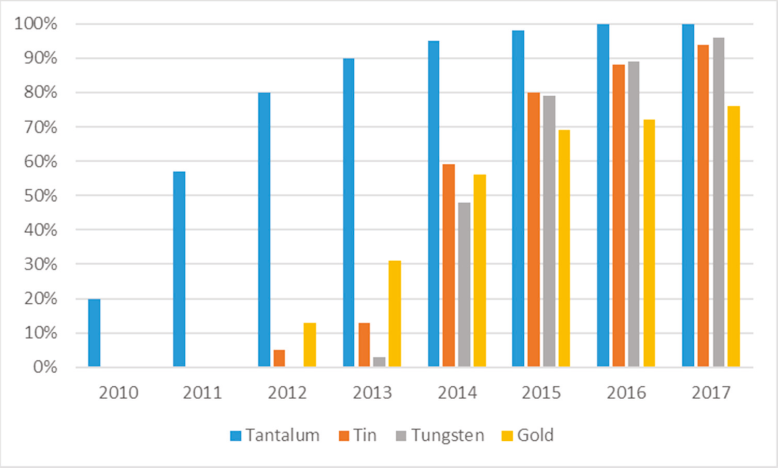

Figure 2. The fraction of global smelters and refiners conformant to international due diligence standards. Includes suppliers listed by the Responsible Minerals Initiative, the Responsible Jewellery Council, and the London Bullion Market Association (N = 323 facilities at end of 2017).

The Conflict-Free Sourcing Initiative was founded in 2008 by members of two industry associations, the Electronic Industry Citizenship Coalition and the Global e-Sustainability Initiative, largely involving multinational brand name electronics firms [49]. The roots of the effort go back to 2007 when a working group was struck to respond to claims made by civil society groups [50]. By 2017, when the name was changed to the Responsible Minerals Initiative, the business initiative had over 350 members from companies and associations from ten industries (including electronics, automotive, retail, aerospace, apparel, telecommunications, and jewellery). The initiative aims to support company raw material sourcing decisions including regulatory compliance and responsible sourcing from conflict-affected and high-risk areas. The manufacturers and brand-name firms at the downstream end of the metals supply chain paying for membership in the initiative, and they are supported with tools to achieve and information to report on responsible sourcing. This relies on companies at the upstream end of the supply chain: metal smelters and refiners who are encouraged to "participate" in the Responsible Minerals Assurance Process (formally the Conflict-Free Sourcing Program) by implementing due diligence management systems based on the OECD guidance [9]. The program developed due diligence standards for each the four metal industries. Participating companies pay the costs of implementing their own due diligence systems and usually pay for assurance audits. The Responsible Minerals Initiative provides training materials and guidance, manages third-party stakeholders, and maintains a list on their website of smelters and refiners who are conformant to each due diligence standard [49].

Central to the current study was the Responsible Minerals Initiative smelter engagement team, composed of individuals from about fifty member firms who performed outreach to metal smelter and refinery companies. The team was created in 2013 but its efforts became more earnest in 2014 and 2015 after the U.S. Dodd–Frank Act rule reporting requirements came into effect.

3.1. Descriptive Data on Smelters and Refiners

The first stage of the research design involved investigating the pattern of smelter and refiner participation into the program. The master smelter database, provided by the Responsible Minerals Initiative, describes approximately 3000 entities, names, and brands that are associated with 3TG suppliers. Over the years, the Responsible Minerals Initiative determined more than 2000 of these names not to be actual smelters or refiners. As of late 2017, about 400 names remained under investigation but they were of low likelihood to be eligible smelters or refiners. The remaining 323 facilities constituted the population of known and confirmed smelters and refiners and, of these, 87% participated in a due diligence program and, as of late 2017, 78% had achieved conformance (see Table 1).

Information was consolidated and formatted into timelines for each of the four metal industries. Documents from the program included training materials, the smelter database, templates used for emails and letters, program performance metrics, and summary reports. (In a parallel study, our research group assessed business characteristics for 212 of these facilities, including firm size, location, and management system experience [14].) Key information on the 323 facilities included dates that smelters and refiners started participating in the program and outreach efforts that were made by member firms on behalf of the program to engage with suppliers and encourage them to participate in the program. Central to the analysis was the status of each facility: the date of commitment to participate, audit date, and date of conformance. Timelines were annotated with dates of external events (like regulation) and activities internal to the initiative (like creation of the smelter engagement team). The four timeline figures were used as a reference to support interviews with conflict mineral managers in downstream manufacturing firms.

3.2. Interviews with Downstream Firms

Semi-structured interviews with conflict mineral managers in downstream firms sought to expose how manufacturers engaged with, and persuaded upstream metal companies to participate in, due diligence programs. Interviewees were recruited through a combination of convenience sampling and purposive sampling. Based on the recommendation of the Responsible Minerals Initiative manager, twelve candidates were invited to participate in the study, with six interviews accepting and interviewed between January and March 2018. Interviewees were current or previous members of the supplier engagement team and experts in conflict minerals. These individuals typically had 10–15 years' work experience in supply-chain or corporate social responsibility functions in multinational electronics firms. Interviewees were drawn from a cross-section of Responsible Minerals Initiative member companies, and they had experience working in different regions and different 3TG industries.

The theoretical basis used in designing the interviews was from Sauer and Seuring, who provide a framework for supply chain management of mineral supply chains [37], which was selected given its roots in sustainable supply chain management scholarship [26]. Their categories include government interventions, strategic orientation, supply chain continuity, collaboration, risk management, and proactive management. The timelines from the descriptive data analysis were provided to interviewees ahead of time as a starting basis for interview discussions. Interview questions helped to contextualize the timeline analysis, and they were designed to expose nuances and challenges of lower-tier supplier engagement (Appendix A). Interviews were 30–60 minutes over the telephone, which were then transcribed and imported into QSR NVivo, a data analysis software. Following Miles and Huberman [51], first-order concepts were identified using open coding, which were then grouped into second-order themes through axial coding. We then discussed emergent concepts and the connections between them in relation to the extant literature, specifically Sauer and Seuring's framework, with new concepts being created where necessary.

A number of measures were taken to address concerns regarding the validity and reliability of data and results. Construct validity was enforced by using a preexisting research framework. Our dyadic approach linked data on upstream sellers of raw materials to independent data collected from downstream buyers in the supply chain. Internal validity was supported by selecting key informants with first-hand knowledge of the engagement processes. External validity was enforced given inclusion of the whole population of suppliers across the four parallel case industries. Reliability was assured given the sequential roles of the researchers in undertaking the research, as well as extensive discussions related to emergent concepts, which were discussed between researchers until consensus was reached. Furthermore, the use of a mixed method design allowed for the comparison of qualitative and quantitative data [52] from both the interviews and the timeline analysis, revealed a convergence of results. Fuller information on the methods, including more data on the timelines for all four metal industries, is provided in the master's thesis completed by one of the authors [53].

4. Results

The industry timelines (Figures 3–6) provide graphical summaries of supplier engagement for the four metal industries, showing patterns initial participation, growth in participation, and abatement of new participation. In the case of tantalum, the program achieved 100% smelter participation (allowing for some ebb and flow as companies do change management or ownership). For tin and tungsten industries, the total participation exceeded 80% by 2016 and continued to climb gradually; whereas, for gold the total participation seemed to have plateaued around 70% in 2015 (see Figure 2). Based on these results and supplemented with information from the interviews (identified as P1–P6), a narrative was formed on smelter and refinery participation in due diligence programs.

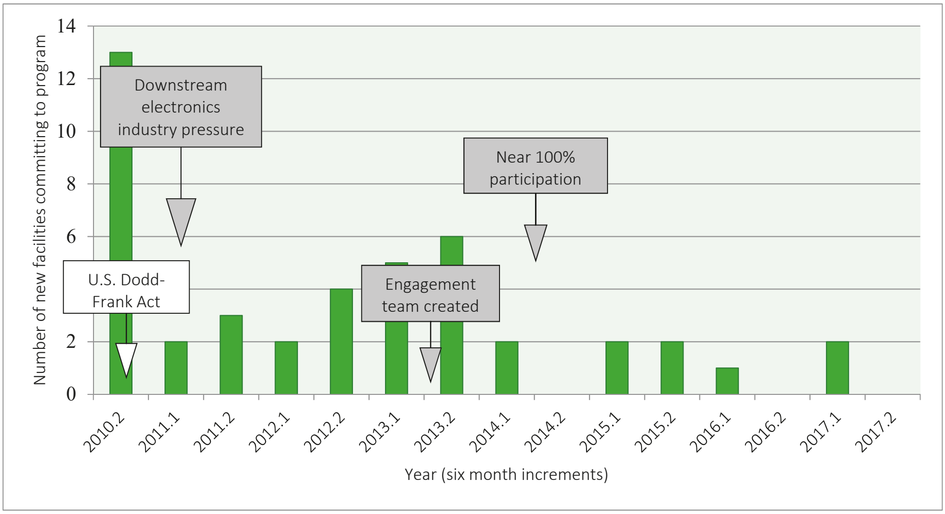

Figure 3. Timeline of tantalum industry metal producers joining due diligence program, to 100% of known facilities engaged.

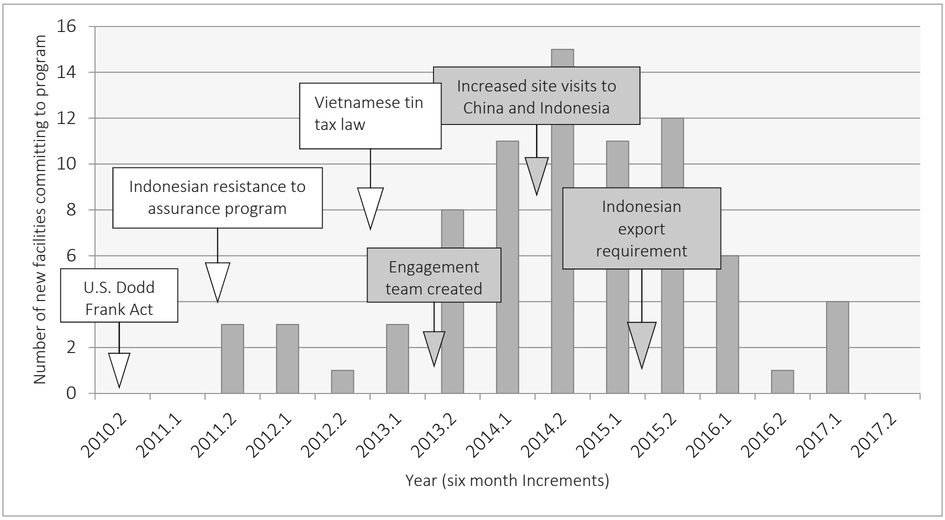

Figure 4. Timeline of tin smelters and refiners joining the due diligence program, to about 95% of known facilities engaged.

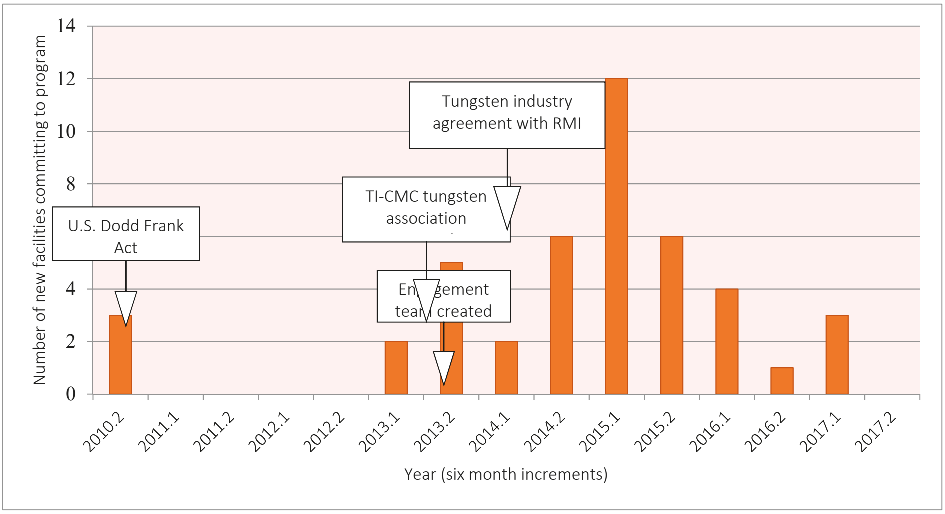

Figure 5. Timeline of tungsten smelters and refineries joining the due diligence program, to 96% of facilities engaged.

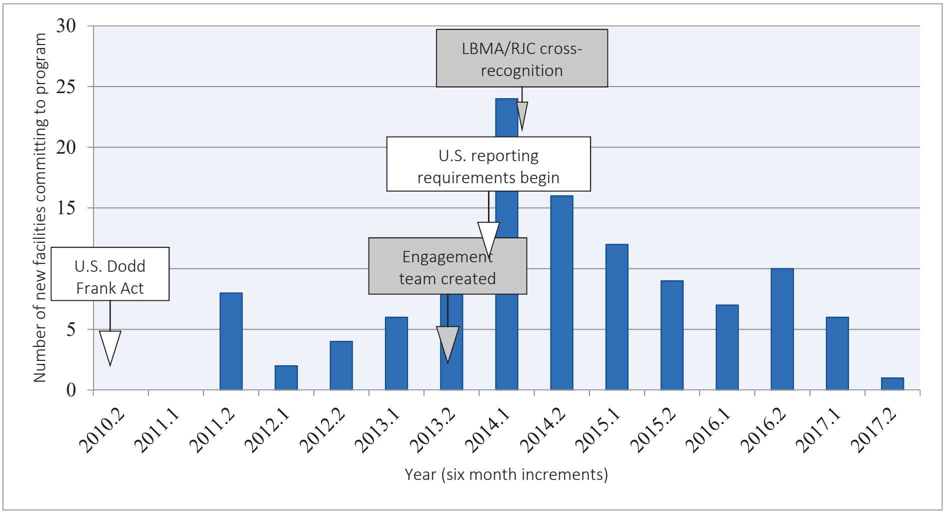

Figure 6. Timeline of gold refiners joining Responsible Minerals Initiative, Responsible Jewellery Council and London Bullion Market Association due diligence programs, to about 70% of large gold facilities engaged.

About 2007, manufacturers realized they would need to understand sources of 3TG raw materials in their supply chains. Some of the larger electronics firms began sending enquiries to their suppliers, in hopes that their requests would penetrate through multiple tiers. Several issues became apparent:

- tracing specific chains of metals all the way back to mines was largely infeasible (as discussed above, for physical and business reasons, see for example [34]);
- identification of mineral processors was confusing because there was blurring of roles and names of mines, smelters, refiners, alloy makers, metal casters, fabricators, traders, and brands; and,
- end-product manufacturers in electronics share from many of the same 3TG metal suppliers.

Based on this, it was logical that downstream firms collaborate to better understand their lower-tier suppliers and to manage responsible sourcing. The Responsible Minerals Initiative was created and supplier engagement began. Early consultant analysis [34,54] suggested that refiners and “smelters were the pinch point in the supply chain” [P4]. They purchase mineral concentrates from mines or through traders, convert them to refined metals and metal chemicals, which then are sold to downstream manufacturers of parts and components. Smelters and refiners also purchase post-industrial and post-consumer sources that are recycled in the same facilities as process primary feedstocks. Smelters and refiners thus constitute a finite group of identifiable facilities (see Table 1), mostly large-scale capital intensive metallurgical operations. “The smelters, the refiners, that we work with are pretty [deep in] our supply chain, so they are not our immediate next supplier, they are maybe 8 or 9 down the supply chain“ [P3].

Engagement of smelters and refiners was part of a three-stage process: (1) identification of potential facilities, (2) validation of alleged facilities to determine the legitimacy of smelters or refiners at the chokepoint, and (3) outreach to encourage facility participation in the due diligence program.

1. Identification

To identify metal smelters and refineries, the Responsible Minerals Initiative developed a standardized supplier survey for members in 2011. The survey provided common definitions, standard smelter and refinery names, and fields to characterize suppliers (location, capacity, ownership, etc.). This process also relieved survey fatigue experienced by suppliers. With the creation of the smelter engagement team in 2013, the program “started to be more tactical and strategic about engagement” [P4]. Supplier identification efforts were coordinated: downstream firms shared and aggregated survey results, then met to coordinate the identification of potential smelters and refiners. However, because surveys needed to be relayed from individual member firms back up the chain to identify metal processors, and then returned downstream via the same chain, interviewees noted that there were poor return rates (in the order of 1%). It was “tricky because we are so far removed from the smelter itself and even our direct suppliers are removed from the smelter itself so that can be challenging twisting through the supply chain” [P6]. Curiously, this approach meant that manufacturers identified their 3TG suppliers without actually knowing how their supply chains were connected. Supplier surveys were anonymized at each tier of the supply chain to preserve business confidentiality between competitive suppliers and prevent line-of-sight visibility to smelters and refiners. Survey results were additionally anonymized by the program, who managed the consolidated database.

2. Validation

Validation was necessary after suppliers were identified. Numerous product brand names, marketing and distribution companies, differences in ownership and location, and confusion about what actually constitutes a metallurgical processor complicated the process of identification and qualification. The smelter engagement team clarify which smelters and refineries were targeted (e.g., a facility needed to have the technical ability to process primary mineral concentrates) and performed additional enquiries through industry associations to confirm processors. Nonetheless, with enquiries aggregated among downstream firms and repeated annually, the efforts began to “build supply chain visibility” [P6]. Over the years, the collaborative effort developed a reliable database of qualified smelters and refiners for each of the four metals, which is updated regularly and provided to Responsible Minerals Initiative members.

3. Outreach

Priority for outreach was to facilities that were identified most frequently in member supplier surveys. “Smelters … that weren’t participating, would get letters, and lots of letters, and finally if you start to get enough letters from all these big brand name companies, I think that helped drive some of the participation. And so if you look at both tungsten and tin, you see that bump in 2013 about the time SET got started” [P3]. “After we conduct the survey we find smelter contact information and directly go talk to them, and . . . engage with the smelters. So we either try to email them, try to call them, and then meet them in person. We find that's the most effective way to get them engaged and this can be done by going directly to the smelter facilities" [P6].

Efforts were coordinated to encourage constructive communication and to avoid overloading prospective participants. Depending on the type of company and the region involved, a plan for each supplier was developed. This included coordinated emails, letter writing, and social media, each urging the smelter to participate in the program. Messages could be escalated depending on the responses or commitments received (or not received) from the supplier. Importantly, a single-point-of-contact person was designated for each facility, to mitigate overloading a particular supplier with requests or mixed messages, and to provide a friendly liaison who could encourage program participation. "[W]e found that sometimes when too many companies are trying to reach the smelter or communicating with the smelter it can cause confusion and they eventually stop responding . . . it was probably better to assign one member company person to engage with the smelter" [P6].

Escalating their efforts of coordinated persuasion, manufacturers began to visit suppliers in-person at smelter facilities around the world. Depending on the culture and language and the nature of firms involved, the team would work with translators and a member of the engagement team might do a site visit. Other tactics included attending metal industry conferences and working with industry associations. This action conveyed the gravity and urgency of the conflict mineral problem, and was very effective: "So in terms of how smelters become active I think the most important thing is being very engaged and having not only your company brand but establish, but trying to establish a face-to-face relationship with the smelters" [P6]. "Thus downstream firms overcame barriers of distance, "breaching language, breaching communication or going to those places physically" [P6].

Somewhat surprisingly, top-tier manufacturers were visiting upstream companies who were not their own suppliers. For example, one target group was tin smelters in Indonesia, many of which are small in size. At the extreme, this meant a representative from a U.S. multinational electronics corporation travelled to the island of Belitung, Indonesia to knock on the door of a family-owned, 20-employee tin smelter. Another effort focused on tungsten facilities in China, many of which are located in Ganzhou, China. Gold refiners in Korea were another target group, which include numerous small operations doing recycling from manufacturing industries in that country.

According to a survey by the Responsible Minerals Initiative covering about one-third of the audits done from 2015–2018, metal suppliers expressed that they participated in the program because of their own company policy (85%), because of customer requests (80%) and because of requests from end-use manufacturers (50%). The last point aligns well with data in the timelines (see Figures 3–6) showing that new participation of suppliers grew by 35%, 85%, 90%, and 80%, respectively for tantalum, tin, tungsten, and gold, following the creation of the supplier engagement team in 2013.

The program offered supplier development resources and also provided financial assistance to suppliers. Education and training were delivered in at least eight different languages, including online, seminars at conferences, and workshops for targeted groups, like tin producers in southern China. A fund was created, financed by individual member firms, and used to offset the costs of a supplier's first audit, significantly reduced the financial barrier to smaller facilities to participate in the due diligence program. More than half of the conformant facilities benefited from the fund, which distributed approximately $2 million up to 2018: "you combine that with the face-to-face interaction and the hand holding of getting them ready for the audit then they're more likely to be successful" [P6]. Interviewees and program managers expressed general satisfaction in the performance of the program in reaching suppliers over ten years of operation.

4.1. Tantalum

Smelters and refiners in the tantalum industry were quick adopters of due diligence systems for responsible sourcing (Figure 3), as the majority of producers achieved conformance to the program in the first two years. Several factors were involved: electronic capacitors account for a high proportion of tantalum use, the DRC is a major region of metal supply, capacitor firms are closely aligned with the electronics industry, many midstream and downstream firms are U.S.-based and were therefore immediately subject to the Dodd–Frank Act rule, most electronics corporations already had strong corporate social responsibility commitments, and the upstream tantalum industry association rallied successfully around the issue.

As apparent in Figure 3, the supplier engagement team did not contribute significantly to engagement in the tantalum industry. Unlike the other three metal industries, "the electronics industry had the leverage and the purchasing power to influence [and] ... apply the pressure that we could" [P4]. After a couple of the leading capacitor manufacturers joined the program, and with the support of brand-name computer firms that faced reputational risks there was rapid acceptance in the industry for responsible sourcing standards written by the downstream initiative. "The tantalum industry was very a vicious industry without much collaboration. But when this came out, and this is where we saw a lot of collaboration occurring" [P4].

Of interest for tantalum, one interviewee referred to more advanced responsible sourcing efforts that were built off the collaborative responsible sourcing initiative. A "closed-pipe" system was described that directly connects a specific mine in DRC, where conflict was not a problem, to a conformant smelter, for example in China, to a capacitor manufacturer in the U.S., to a top-tier manufacturer of electronics. Thus material was securely and assuredly moved from extraction to end-product.

4.2. Tin

The tin industry, conversely, was not motivated by the Dodd–Frank Act (Figure 4) and the role of the engagement team was significant. Indifference to the U.S. conflict minerals rule was understandable, given that the vast majority of tin processors are outside the U.S. (e.g., Indonesia, China, Peru, Bolivia) and the bulk of tin ore is sourced regionally, far away from the problems of Central Africa. Although several large producers did participate early, there was "slowness given the number of tin smelters that exist ... [and] a lot of pushback from Indonesian tin smelters [and] a lot of pushback from [industry associations]" [P4].

The smelter engagement team played an important role in engagement tin smelters and refiners in due diligence programs. "What happened was these smelters started receiving letters ... asking them what they know about responsible sourcing, have they done anything in the past" [P3]. However, it took more significant efforts to achieve commitments from tin industry actors. "[T]in smelters started getting active when we as member companies started visiting smelters for the program ... I think the [engagement] team played a major role, face-to-face contact" [P3]. Regional outreach efforts resulted in participation by blocks of companies starting in 2012, including major refiners in Thailand, Malaysia, Peru and Bolivia. Indonesia and China were high-focus areas. "[We] recognized that its very very important, especially in Indonesia culturally to have that face to face relationship [and] stay in touch with the smelter" [P6]. Participation of small companies in Indonesia was particularly advanced in 2015 after the government-run Indonesia Commodity & Derivatives Exchange (ICDX) made compliance to the tin due diligence standard a requirement for tin export. In China, the world's largest tin refining nation, the program engaged with larger state-owned firms and with government representatives, who provided an initial door for acceptance in that country. The program continued to work on the participation and the conformance of tin smelters and refiners in China as late as 2018.

4.3. Tungsten

Tungsten smelters and refiners took longer than the other metal industries to become active in due diligence efforts (Figure 5). Although a small number of U.S. and European tungsten producers participated early-on, there was generally low interest: "Tungsten was really late to the table and such a small amount of tungsten actually came out of the region, they just didn't really want to engage" [P4]. Program members constituted a relatively small portion of the tungsten market. "The electronics industry just did not have a lot of leverage over tungsten" [P4]. Moreover, given that a tiny fraction of tungsten is sourced from Central Africa (less than 2%), the lack of interest by tungsten producers was understandable.

A significant breakthrough occurred in 2013. The engagement team became more active. Numerous site visits were made by program representatives to tungsten facilities, many in China. Knowledge was gained both by the downstream manufacturers and by companies in the metal industry; interviewees spoke of trust-building to address concerns with "business confidential information [and] lack of awareness" [P5]. Concurrently, a new tungsten industry association was formed to facilitate responsible sourcing (the Tungsten Industry-Conflict Minerals Council). At the end of 2013, an agreement was struck between tungsten council and the Responsible Minerals Initiative. Tungsten producers who are members of the council are provided funding by the downstream program for facility audits and they are given a three-year (instead of one-year) audit cycle, and the tungsten due diligence standard provides streamlined procedures for the tungsten industry.

Notably, after the new agreement came into effect, competitive pressures in the tungsten industry appeared to motivate other tungsten producers, even those who were not council members, to participate in the due diligence program. Given that approximately 80% of tungsten production takes place in China, interviewees observed that the program was particularly successful in gaining traction in that country—far from the U.S. Dodd–Frank Act and European pressures.

4.4. Gold

Although the gold timeline (Figure 6) looks similar to the other 3TG materials, the gold industry operates unlike other markets. As observed by one interviewee: "gold is a completely different animal" [P6]. Gold behaves more like currency than a metal. It is mined wherever possible, all around the world, and all but the smallest country has a gold refinery, often associated with the national mint. The value per mass is high, thus "it's really hard to track and the quantities are much smaller for bigger profit" [P6]. Gold is readily recycled, resulting in significant mixing of old and new sources. Because of its value "it's also used as currency, its used to wash money" [P4]. And, as several interviews noted, "they're not paying the taxes on it, so miners actually get more per gram of gold through illegal channels than they do through legal channels" [P4].

With respect to encouraging participation in the Responsible Minerals Initiative due diligence program, "gold smelters and refiners were the most challenging to engage, and where [supplier engagement] tactics were the least successful" [P1]. "Gold is one of the hardest ones, because we don't really have that much gold in the electronics industry, so it's hard for us: we don't really have any leverage to convince them" [P6]. For example, it was especially difficulty in convincing refiners who source gold from mines in China to "join an American program that determines whether they source from Africa" [P2].

To make gains on responsible sourcing, the Responsible Minerals Initiative relied on programs that were developed by two other industry associations, the Responsible Jewellery Council and the London Bullion Market Association. Although a significant volume of tantalum and tin go to electronics, about 90% of gold goes to non-industrial uses, such as in jewellery and bullion (including coins, gold bars, and ingots). To achieve greater reach relevant to all gold end-uses, the three associations agreed to cross-recognize their due diligence standards. The London Bullion Market Association is particularly relevant, as it includes more than one-hundred large gold refiners that, since 2014, must each maintain a responsible gold certificate that supports due diligence with respect to risks, including conflict, human rights abuses, terrorist financing practices, and money laundering [55]. This certification requirement led to a clear uptick in conformant facilities, starting in 2014 (see Figure 6). These partnerships allowed for electronics firms to overcome their inability to apply market pressure onto gold refiners.

Responsible sourcing remains an on-going challenge in the gold industry. From a transparency perspective interviewees noted that the commodity exchanges represent an important barrier. For example: "Within China, the Shanghai Gold Exchange, the gold would go in and go out, there was no tracking of who got what gold. . . . if you tried to chase the gold supply chain, it was always stopped at the exchange, and so you really didn't know who your refiners were" [P4]. Non-conformant facilities are known to be all over the world (Mexico, Middle East, China, India, etc.) and they are often in regions where there is little or no market incentive to participate in due diligence programs.

5. Discussion

This study explored how global manufacturing firms engaged with suppliers in mineral supply chains to enable responsible sourcing. The research responds to Carter, Rogers, and Choi, who asked how organizations might "manage physical supply chains that reside beyond the visible horizon" [8] (p. 94). Evidence revealed how top-tier firms in electronics and other sectors overcame barriers of geographic distance, physiological distance, and cultural distance in identifying and engaging with 3TG suppliers. General strategies for sustainable supply chain management, like communication, education, and development, and compliance approaches are relevant to all suppliers [28], but for suppliers over the visible horizon [8] management needs to include engagement steps, including identification, validation, and outreach.

The concept and value of a supply chain chokepoint at smelters and refiners [13] has been confirmed. The chokepoint is where there is a concentration of firms in the upstream supply chain where sustainable management practices can influence lower-tier suppliers. This observation supports theory on diamond-shaped supply chains [36] and specifically confirms what Seuring and Sauer refer to as "upstream focal firms" [5,37], who control the integrity of mineral feedstocks entering mineral supply chains.

A novel contribution of this study is what we call the "deep supplier". A deep supplier is defined as a lower-tier supplier—beyond the visible horizon of top-tier firms—whose position at a supply chain focal point affords them leverage over their suppliers. In the context of 3TG metals, the management and purchasing actions of deep suppliers was shown to have a significant effect on the sustainability of the mining practices and hence contribute to overall supply chain sustainability. We believe this concept could have application beyond the 3TG metals, to other industries whose structure also reveals lower-tier supply chain focal points.

Surprisingly, lack of supply chain transparency does not present an impossible barrier for multinational manufacturers to manage deep suppliers. We observed top-tier firms "jumping the chain" to engage with deep suppliers, who are beyond their visible horizon and who may—or may not—be physical suppliers to all top-tier firms. The did this collaboratively, working through the standards program, a business-led initiative. Although individual manufacturers could conceivably invest greater resources to discover more about their mineral supply chains, it was both effective and sufficient for top-tier firms working together to jump-the-chain to manage deep suppliers.

5.1. Contribution to Theory

This study contributes empirical evidence to theory on sustainable supply chain management in multi-tier supply chains. Figure 7 depicts a conceptual framework of engagement with deep suppliers. Whereas, the theoretical work of Tachizawa and Wong [3] suggests four management practices by which top-tier firms engage with lower-tier suppliers (direct, indirect, "work with third party" and "don't bother"), we have identified a potential intermediate practice, to "work with second party", which more accurately describes the role of companies working in business-led efforts, like the Responsible Minerals Initiative. The members of the initiative were highly active in parts of the operation of the initiative, including efforts to engage suppliers. "Work with a second party" captures the practice of jumping-the-chain, whereby a top-tier firm works with the initiative and in collaboration with competitors to achieve engagement. This differs slightly with Sauer and Seuring [35], who describe a mechanism of cascaded multi-tier sustainable supply chain management that links between downstream and upstream parts of mineral supply chains, in that, in our conception, the role of the second party is pivotal. Results are supportive of Hofmann, Schleper, and Blome, who describe due diligence in multi-tier supply chains [6].

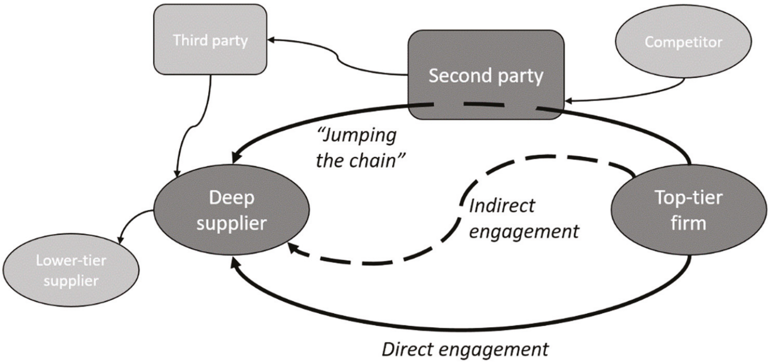

Figure 7. Types of supplier engagement.

Our results contribute empirically to the limited body of research on engaging lower-tier suppliers in sustainability management. Gong, Jia, Brown, and Koh suggest a number of supply chain learning stages [31], which were apparent in our study, including top-tier firms working in breadth with partners and working in depth to learn more about lower-tiers. By sending requests to their immediate suppliers as a means of indirect engagement, manufacturers learned the identity of deep suppliers. Thus, even with limited knowledge of lower-tiers, by partnering and collaborating focal companies were able to apply a direct approach to manage deep suppliers. Additionally, although well observed in the direct management of first-tier suppliers [29,56,57], we add to the understanding of how focal companies work directly with lower-tier suppliers and with strategic partners to establish governance mechanisms to manage distant suppliers [30,31]. Beyond standards and compliance, "contributive" strategies [57] include training, financial incentives, and other assistance intended to develop supplier risk management capacity. Interviewees identified more "pro-active" strategies [57] undertaken by manufacturers for supply chain sustainability and risk mitigation, for example "closed-pipe" material supply networks (see Figure 7) provide dedicated conflict-free sources of tantalum to end-users who are highly dependent on this critical material [5,58].

Results also confirm contingency variables that Tachizawa and Wong suggest affect supply chain relationships in multi-tier supply chains [3]: each of the four metals is "critical" to electronics and other high-tech products and manufacturing; top-tier manufacturers are "dependent" on the concentration of smelters and refiners at the chokepoint; there is significant "stakeholder pressure" and reputational risk for top-tier firms; "industry dynamism" of smelters and refiners is low, as these facilities tend to be technically complex, capital intensive, and permanent; there is a significant physiological, geographic, and cultural "distance" from mostly-Western top-tier firms to many smelters and refiners in developing countries; and, top-tier firms have limited in their familiarity and industry "knowledge" of smelting and refining at deep suppliers. To mitigate this last variable and to engage deep suppliers, the Responsible Minerals Initiative relied significantly on metal industry associations and other upstream parties for metal industry expertise.

The study indicates how top-tier firms exercise power in multi-tier supply chains and how lower-tier suppliers responded to pressures of sustainable practices. Results support prior considerations on how the power of multinational firms is focused to influence lower-tier suppliers [3,6]. The extent to which downstream buyers influence upstream producers differs according to leverage available. In the case of tantalum, given that electronics applications account for the majority of use, top-tier firms used their economic power to leverage metal producers to implement responsible sourcing. For tin and tungsten, where market leverage was lower, power was exerted more softly through non-economic persuasion of deep suppliers. Coordinated letter-writing and site visits from "big brand name companies" helped to overcome supply chain distance and improve industry knowledge. To reach and motivate gold industry actors, even more indirect efforts were needed, primarily via partnering with third parties in the gold bullion and jewellery industries that had more direct power to influence gold refiners.

There is varying understanding of supply chain transparency. Hofmann, Schleper, and Blome describe four practices that increase transparency along supply chains [6]: certification of firms, chain-of-custody along the value chain, traceability of materials, and due diligence of firms. Using their terminology, full transparency in the supply chain would include clear line-of-sight upstream, and this would require chain-of-custody traceability of raw materials backwards from end-users to source. However, in this study, top-tier firms described a more limited transparency that provides identification of deep suppliers but without line-of-sight traceability through the supply chain. To encourage due diligence management at deep suppliers, manufacturers gathered information to identify smelters and refiners, but they did not have enough knowledge on the operating structure of those supply chains to their supply chains link-by-link. Thus, in practice, firms are prioritizing due diligence over traceability. This finding is consistent with Kim and Davis who showed that very few corporations filing under the Dodd–Frank Act rule claim to know whether their products are "DRC conflict-free" [32]. Knowing one's suppliers by name is not sufficient to know the source of materials entering one's specific products.

Traceability appears to be more complex and costlier than due diligence alone. Materials that were produced by lower-tier suppliers can be tracked *forward* through multiple tiers in the supply chain to downstream manufacturers, but firms need separate instruments and more developed systems to trace materials *backwards*, for example, to confirm suppliers in the chain, or to know the upstream sources of food that is subject to a health recall [39]. For minerals traceability, Apple, a large electronics firm, began tracing its supply chains of tantalum, tin, tungsten, and gold in 2010. This involved looking upstream from manufacturing back to smelters. However, it was not until the end of 2016 that Apple could claim that all its known 3TG suppliers were participating due diligence programs [10]. Traceability requires significant information and more sophisticated systems. Further research is necessary to tease apart and better understanding the nuances of responsible sourcing concepts, including transparency, due diligence, tracking, traceability, and chain-of-custody.

5.2. Implications for Practice

Responsible sourcing has emerged as an expectation of producers and users of metals and minerals. Transparency can improve confidence on sources of materials, which may improve security of supply, by knowing more about both physical flows and business information on actors in global markets. Without knowing one's suppliers, there is concern that things will be out of compliance to regulations or fail in quality but, more broadly, it limits sustainable supply chain management and the mitigation of environmental impacts and social problems that may be present in distant global supply chains. Results here have suggested that simply by being known to downstream customers (and therefore visible to other stakeholders), there is pressure on deep suppliers to improve practices.

This study provides insights that may support responsible sourcing and supply chain management for a larger set of important materials. Two of the four conflict minerals (tantalum and tungsten) are commonly characterized as critical raw materials [7,19] that are paramount in low-carbon and other technologies yet also present geopolitical supply-risks. The Responsible Cobalt Initiative due diligence standard targets an important critical metal that also presents responsibility concerns. The London Metal Exchange expects responsible sourcing standards to be in place for the major base metals [11]. The exchange specifies physical standards and it is the main global price-setting platform for aluminum, copper, zinc, nickel, lead, tin, molybdenum, and cobalt.

Moreover, the goals of responsible sourcing are expanding. Initial concerns were on conflict (and focused on the DRC), but the OECD guidance broadens consideration to "conflict-affected and high-risk areas", which cover a variety of human rights, conflict, and governance concerns [9]. The cobalt standard aims to improve responsible sourcing that includes labor conditions, like the prevention of forced labor and better health and safety [59]. Other programs hit on additional aspects of sustainable development, notably in its responsibility standard the Aluminium Stewardship Initiative refers extensively to environmental objectives and to the rights of indigenous peoples [60].

Several study informants made note of the success of supplier engagement and due diligence implementation in China. Reasons for this success were several, and they may inform other efforts in responsible sourcing, like those for sustainable wood and fisheries that have been less successful in China (see [5]). First, given that China is important not just to upstream processing of metals (see Table 1), but also to midstream manufacturing and downstream assembly of electronics, member firms could exercise market leverage (particularly of tantalum and tin suppliers). Second, was the ability to bridge cultural distance by member companies with significant local presence. Third, firms invested significant individual and collaborative resources, including repeated site visits and connections to partner organizations such as Chinese industry groups and government agencies. It appears that Chinese authorities accepted the value of responsible sourcing and, perhaps more importantly, accepted the value of third-party assurance of responsible sourcing. The success carried to cobalt supply chain responsibility, which started operation in 2018 as a collaboration of the Responsible Cobalt Initiative, the Responsible Minerals Initiative and the China Chamber of Commerce of Metals, Minerals & Chemicals Importers & Exporters [59]—which is important given that China is a major cobalt processor and a maker of electric vehicle batteries.

The current research has elucidated strategies and mechanisms that top-tier firms use to identify suppliers of material resources and encourage lower-tier suppliers to implement due diligence systems. Top-tier firms are collaborating and "jumping the chain" in order to engage deep suppliers. Results have shown the considerable efforts that top-tier firms have made to discover the identity of companies who are suppliers of 3TG metals: coordinated outreach, face-to-face visits, and direct financial support. Compare this to raw material criticality assessments, which generally use data at the national scale [19,20]. Few researchers have paid attention to managing real supply chains at the firm-level [20–23] at the firm-level resolution shown here for 3TG sources.

Whereas, technical avenues to the critical materials problem, like geological exploration, efficient mining and metallurgy, and materials substitution, are widely touted [7,19], management strategies for mineral governance are less discussed. Firms need to manage risks in mineral supply chains, regardless of whether risks are associated with supply disruption, with conflict or with environmental hazards. One approach is simply to change the sources of raw materials, to shift sourcing away from high risk countries and companies. However, to do this, firms need to know where materials are actually sourced, and this is difficult due to complex long supply chains, multiple processing tiers, independent traders, and long transportation distances. Another difficulty for minor metals, which is a key contribution to the criticality of raw materials, is that there are often a limited number of producers or production concentrated within a region. For example, most tungsten, which is classified as both a critical raw material and a conflict mineral, is mined and processed in one region in China.

In managing risks in their supply chains, top-tier firms have begun to develop systems and risk management approaches, and they participate in audit and certification processes. By better understanding their suppliers, manufacturing firms can "identify and manage critical suppliers" [8] and improve their ability to mitigate sources of supply disruption while maintaining ethical and sustainable sources of raw materials [24]. If a top-tier firm has better knowledge of lower-tier suppliers, it can better assess risks and implement strategies to manage risks.

More broadly, we discern a "responsible sourcing regime" for global governance of minerals and metals supply chains. Businesses are undertaking efforts in responsible sourcing that is guided by high-level norms and policy, which is executed through private-sector governance of minerals and raw materials [19,24,25]. Three levels are apparent: (1) principles and broad objectives like those in the OECD guidance on due diligence; (2) standards and requirements defined by industry-led programs, but also in government regulations like the U.S. and Europe conflict mineral rules; and, (3) company management systems. Firms need to select which responsible sourcing standards they should follow depending on their needs and capacities, and given the particulars of each industry and their position in the supply chain (upstream, midstream, downstream). Consequently, companies at all stages in the supply chain, and across a growing diversity of resource industries, are implementing responsible sourcing policies, procedures, management processes, and reporting systems.

6. Conclusions

Top-tier manufacturing firms collaboratively manage suppliers of critical metals to increase supply chain transparency and implement due diligence to reduce negative social impacts. We used data on real firms to look at both ends of the mineral supply chain. Upstream, we analysed a population of 323 "deep suppliers"—our term for lower-tier metal producers who are critically positioned to mitigate the conflict mineral problem. Downstream, we conducted interviews with six conflict mineral managers in multinational manufacturers who are end-users of tantalum, tin, tungsten, and gold.

Results showed both expected and novel tactics used to reach suppliers and manage risks in mineral supply. Manufacturers work collaboratively through industry associations to identify, validate, and engage lower-tier suppliers—targeting deep suppliers and persuading them to conform to responsible sourcing standards. Surprisingly, we found that manufacturers do not need line-of-sight visibility to lower-tier suppliers in order to do sustainable supply chain management; rather, global manufacturing firms "jump the chain" to engage directly with deep suppliers at the supply chain chokepoint. This work has contributed empirical evidence to understanding multi-tier supply chains, showing how power is exercised by top-tier firms to manage deep suppliers and to reach suppliers both directly and indirectly, and has helped to understand mechanisms for supply chain transparency.

Due diligence has emerged as an approach that is expected of companies, both upstream and downstream, involved in mineral supply chains where there is a risk of conflict, human rights, governance, or other concerns. For tantalum, tin, tungsten, and gold, the majority of smelters and refineries have implemented due diligence management systems. Responsible sourcing programs like the Responsible Minerals Initiative, the Responsible Jewellery Council, and the London Bullion Market Association have engaged hundreds of companies around the world.

The major limitations of this study are associated with the framing of the research and potential bias in data. The timelines that were developed relied on information provided by one industry association and cross-checked against industry and public information. We did not consult with suppliers or with other due diligence programs that may have differing perceptions of engagement practices. There was a potential selection-bias associated with interviewees. These persons may have skewed positive perspectives regarding their own efforts and programs.

Responsible sourcing, particularly of minerals and metals, is new and consequently numerous avenues for future research are available. Manufacturers have shone a light on deep suppliers, encouraging improvements in social aspects of companies and communities in which they operate. Theoretical work is recommended on the responsible sourcing regime for global governance of minerals and metals supply chains. Specifically:

- Further investigation might consider environmental conditions or management performance of lower-tier suppliers who have no previous experience in corporate social responsibility. What have due diligence management systems done to change deep suppliers?
- There is currently significant company implementation of the five-step process defined in the OECD guidelines. Consequently, future researchers should look for new data and public reports by various companies positioned at points along the supply chain.
- As data become available on due diligence efforts in other industries, and with different objectives, new research questions and comparisons can be considered for conflict minerals, critical raw material, and base metals.

- On a more theoretical level, concepts like transparency, responsible sourcing, and due diligence have just started to gain research interest [6]. These concepts and their practical implementation need additional clarification in future research.
- The impacts of governance initiatives related to mineral and metals are poorly studied, partially because they are relatively young but also given a lack of data and methods [25]. Practical research is possible based on longitudinal data that are available since the Dodd–Frank Act was passed in 2010 on firms and industries, and at national and global scales.

Lastly, it should be emphasized that responsible sourcing and due diligence practices of companies cannot be easily correlated to tangible outcomes regarding mitigation of violence, improved human rights, or governance progress. Continued research, including field work in the DRC and other regions, is necessary to assess real circumstances and guide improvements in mining areas and communities.

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Appendix A

Interview questions:

1. Can you share the story of how this metal/regional group of smelters or refiners became active participants in the Conflict-Free Sourcing Initiative?
2. What were external factors that enabled these smelters to participate?
3. What were external factors that impeded these smelters to participate?
4. What deep supplier engagement tactics did your team try that worked? Why?
5. What did you try that did not work? Why?
6. Do you have any comments or insights regarding the timeline graphs?

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On the Spatial Dimension of the Circular Economy

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Abstract: The concept of a "circular economy", in which material in society is regarded as "a transient phase in anthropogenic resource utilization", is a growing topic for discussion. The primary motivations for supporting a circular economy include a reduction of environmental impacts and conservation of natural resources. Australia is a vivid example of a country whose large metal extraction capacity is not balanced as it has neither an extensive product manufacturing capability nor a large domestic market. Consequently, Australia must rely on the global resource network to achieve circularity and carbon neutrality. This work illustrates this situation with quantitative material flow cycles for Australian aluminum, nickel, copper, zinc, and stainless steel, and comments on the implications of the results for Australia and for circular economy prospects more generally.

Keywords: copper; aluminum; zinc; nickel; stainless steel; sustainable resources

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Highlights

- Australia's metal extraction rates are not balanced by the domestic use of those metals;
- Most domestic metal use in Australia is enabled by imports;
- Australia is far from being a circular economy for metals;
- The circular economy can only be realized at the global level.

1. Introduction

The concept of a "circular economy", in which material in society is regarded as a transient phase in anthropogenic resource utilization, was first formally proposed in 1990 [1] and has come to be regarded in some countries and regions as a politically attractive alternative to the traditional "linear economy" [2–4]. Despite the fact that such a process is, strictly speaking, a violation of the Second Law of Thermodynamics [5], a strong approach to a circular economy may be regarded as a significant improvement over present day practices [6]. The systems perspective of the circular economy implies a preference for repair, reuse, remanufacture, and recycling as strategies to maintain products in service. If this is not possible, the preference is to recycle the product efficiently, rather than dump it as refuse.

Which "economy" does one have in mind when speaking of the circular economy? In fact, is the word economy that is appropriate in this context, given that in a modern economic system each transaction must make sense economically [7,8]? The circular economy approach thus far is clearly focused on materials, and the implication is that it is appropriate to consider it on a regional scale [4,6]—this is probably because Europe is the geographical location of those who have been active in pursuing the concept. It has been observed that it is economically impractical to imagine that a circular economy system could exist within arbitrary geographical borders [9,10] due to globalized systems of production and consumption. Such a system would require each constituency (country, region, etc.) to maintain a complete sequence of industrial capacity for the processing of a full spectrum of materials through every stage of their life cycles [11]. No country or region anywhere in the world meets or could meet that criterion, which requires suitable domestic resources throughout the periodic table, a full manufacturing capability across all aspects of modern technology, and a comprehensive recovery, refurbishment, reuse, and recycling program.

If one grants that the circular economy concept is appealing but challenging, how can a more structured assessment of its potential be achieved? As with many discussions, quantitative information is a useful guide to a more informed perspective, notably for minerals and metals where supply is often concentrated but demand is fragmented and difficult to track. In this regard, national-level life cycles of five materials (four metals and one alloy) are herein presented for Australia, a country with extensive and intensive mining activity, but one that utilizes resources at a very modest level by comparison [12]. This work complements related research in which the criticality of the metals is evaluated [13] and scenarios of feasible future supply and demand of the metals are explored (forthcoming). First, we summarize comments on the circular society potential for each of the cycles and on the environmental implications of the country profile. Then, we explore Australia's options for achieving or approaching a circular society for those materials and reflect on the political and societal aspects of those options. Finally, we outline comments on what these results have to say about the potential for global realization of the circular economy concept.

2. Methodology

A generic diagram for the material life cycle of a metal is shown in Figure 1. The virgin metal enters the cycle at the lower left, moves from one life cycle stage to the next around the circle, ends the life cycle at the bottom right, and, if circularity is to be achieved, returns to the center of the circle and subsequently reenters the cycle to undergo a subsequent use.

Several circled numbers representing metal flows were added to the Figure 1 generic cycle in order to discuss the potential for country-level circularity. Flow 1 represents the flow of metal concentrate, which results from a comminution process that crushes metal-containing ore and performs a rough separation of minerals from gangue by froth flotation (concentrate is the form of a mine's output most often imported or exported). Flow 2 represents the flow of impure metal, from which the anions present in the minerals have been largely extracted in the smelting process, followed by refining the metal to purity, fabricating semi-products (sheets, rod, etc.), and product manufacturing. Flow 3 is the outflow of the target metal in domestically manufactured products. This can be added to or subtracted from flow 4, the amount of the target metal in imported or exported products. Flows 3 and 4 combine to provide the magnitude of flow 5, the amount of the target metal flowing into domestic use. Flow 6 is the domestic recycled flow fed back into the domestic material flow cycle; as Birat [14] notes, it is an extremely challenging step for many metals. However, for a system to completely satisfy circularity for a target metal, flow 6 must be equal to flow 5.

Material flow cycles for selected metals in Australia are constructed upon data generated for this project or as part of more comprehensive projects published previously. The goal for each of the five materials was to generate and/or evaluate sufficient data to construct a cycle on the model of Figure 1 for 2010, the reference year for data consistency across the targeted materials. Doing so required extensive acquisition and vetting of information across the entire metal life cycle from mining to product use to obsolescence to reuse. In the cases of aluminum, copper, nickel, and stainless steel, the analyses were carried out specifically for this project. For zinc, a recently published study provided a 2010 Australian cycle as part of a global zinc assessment [15]. For all metals other than zinc, details of data sources related to Australia and the ways in which material flows were characterized are provided in the Supplementary Information (Tables S1–S5).

The elemental information generated by means of material flow analysis (MFA) constituted the basis for computing the environmental implications associated with a metal value chain. The mining industry is very energy-intensive and, as such, is one of the largest industrial sectors contributing to global greenhouse gas (GHG) emissions [16]. Using gross energy requirements as a proxy for environmental impacts [17], in particular for energy-related GHG emissions, we computed first-order estimates of energy requirements per life cycle stage and for the share of the energy embodied in trade in Australia compared to metal production and consumption. Overall, our model determined the embodied energy in mining, beneficiation, smelting, and refining, prorated for primary and secondary metal inputs. For the fabrication and manufacturing stages, global averages for cradle-to-gate data were used, assuming that the energy required for further processing is negligible compared to that of earlier life cycle stages. Life cycle inventory (LCI) databases and literature were used in combination, as described in the Supplementary Information.

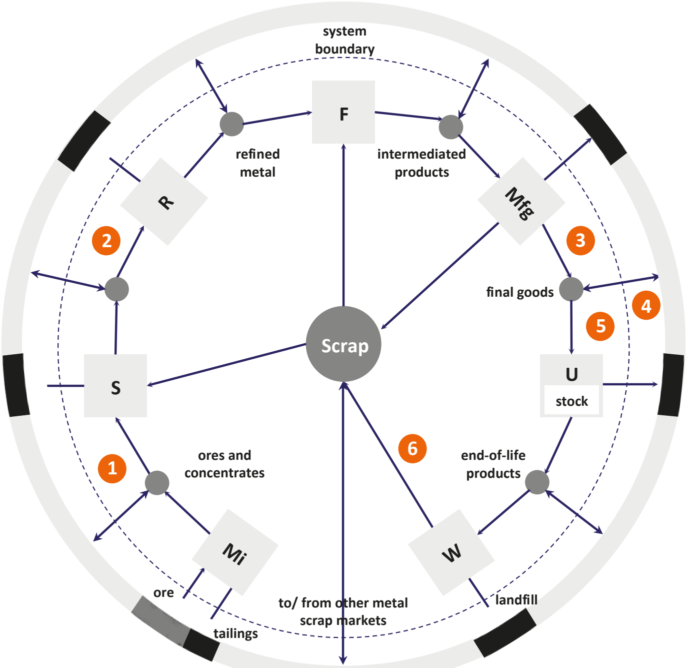

Figure 1. The generic life cycle of a metal at the country level. The dots between the life cycle stages represent international markets through which resources can be imported or exported. In a "circular economy" model, most or all metal would move around the right side of the diagram and through the scrap market back into reuse, while the extraction of virgin resources would be diminished or eliminated. Mi—mining, S—smelting, R—refining, F—fabrication, Mfg—manufacturing, U—use, W—waste management. The circled numbers refer to the discussion in the text.

3. Results

As a first example of our results, Figure 2a presents the Australian material flow cycle for aluminum in 2010. Australia is one of the world's major producers of bauxite and alumina; in 2010, 22,100 Gg Al were extracted in the country from virgin ores. Of that amount, about 2200 Gg were net-exported after mining, 8600 Gg after refining, and 1700 Gg as unwrought aluminum forms. Less than 5% of aluminum originally mined in 2010 entered fabrication for the production of semi-finished goods through extrusion, rolling, foundry casting, and other fabrication processes. A total of 600 Gg of semi-finished goods were then processed into finished goods and, with the additional import of about 300 Gg, entered the use phase. Due to its relatively long in-use lifetime, aluminum embedded in principal end-use sectors such as building and construction and transportation accumulates as in-use stock (400 Gg in 2010). The largest amount of aluminum scrap generated annually derives from packaging and containers. Of the total amount of aluminum scrap (500 Gg), only a minor fraction was domestically processed for recycling, with about 200 Gg of aluminum scrap being exported mainly to China, and more than 200 Gg were disposed of in landfill. Aluminum scrap input to secondary smelting is estimated at about 100 Gg. Even with perfect recycling of secondary sources, achieving a circular economy for aluminum in Australia is inhibited by increasing metal demand and the time delay in scrap generation.

The Australian cycle for copper appears in Figure 2b. About 1000 Gg of copper was extracted and processed from Australian mines in 2010. Primary copper production amounted to 870 Gg, of which more than half was exported. Smelters processed 380 Gg of copper, as well as about 50 Gg of copper from secondary (recycled) sources. Total unrefined copper production was 410 Gg; this amount plus the addition of 40 Gg from net-import of copper anodes resulted in a total copper cathode production of about 450 Gg. More than 60% of the refined copper was exported, and the remaining fraction was processed to create semi-finished goods such as wires and rods, strips, sheets, castings, and tubes. Net-input of new scrap to fabrication was estimated at 10 Gg. Apparent consumption of wrought copper forms amounted to 120 Gg; this flow was processed through manufacturing processes and supplemented with 170 Gg Cu imported in finished goods. Major application sectors included building and construction, infrastructure, machinery and equipment, transportation, and consumer durables. Total copper entering use amounted to 290 Gg. The copper net addition to in-use stock was estimated at 190 Gg, which represents around two thirds of the total flow entering use. At end-of-life, 100 Gg of copper was discarded. Subtracting 40 Gg of copper in exported obsolete products, 60 Gg were processed through the national waste management system. Of that amount, about 20 Gg of copper were not recovered and lost from the cycle.

In Figure 2c we show the Australian nickel cycle. This cycle is quite similar to that of copper in Figure 2b, but shows even less manufacturing activity. In 2010, Australia extracted 210 Gg Ni domestically, of which 170 Gg went into the smelting process. About 60 Gg Ni were exported, while 100 Gg underwent domestic refining and then were almost entirely exported. What nickel is used in the economy is largely contained in products made outside Australia and imported. However, the level of nickel imports is small, and recycling is rather efficient. About 20 Gg Ni entered the use phase, 10 Gg net-accumulated in the anthropogenic reserve, while 10 Gg Ni were generated at end-of-life.

The Australian cycle for zinc appears in Figure 2d [15]. Australia is one of the world's major zinc mining countries, extracting more than 2000 Gg (thousand metric tons) of zinc in 2010. Of that amount, some 1680 Gg were exported immediately after mining and another 310 Gg were exported after smelting. Australian fabrication and manufacturing processes employed less than 10% of that originally mined, and transferred most of that material into use. Because products remain in use for extended periods, discards from use do not balance the input flow, i.e., zinc stock contained in products grows over time. It is clear that even with perfect recycling (which is not occurring now), Australia cannot come close to achieving a circular economy for zinc if it must achieve that goal within its own borders.

The Australian stainless steel cycle for 2010 is given in Figure 2e. This cycle is not for a single metal but for an alloy, one with the approximate composition of 15Cr-9Ni. Australia is a producer of each of these alloy metals, but not of stainless steel itself. However, the country imports stainless steel at the manufacturing stage (100 Gg), and the products of that life stage provide most of the stainless steel for Australian use. Virtually all stainless steel scrap is exported, but need not be, because there is the potential for an Australian circular economy of stainless steel given the approximate balance between flows of stainless steel into and out of use.

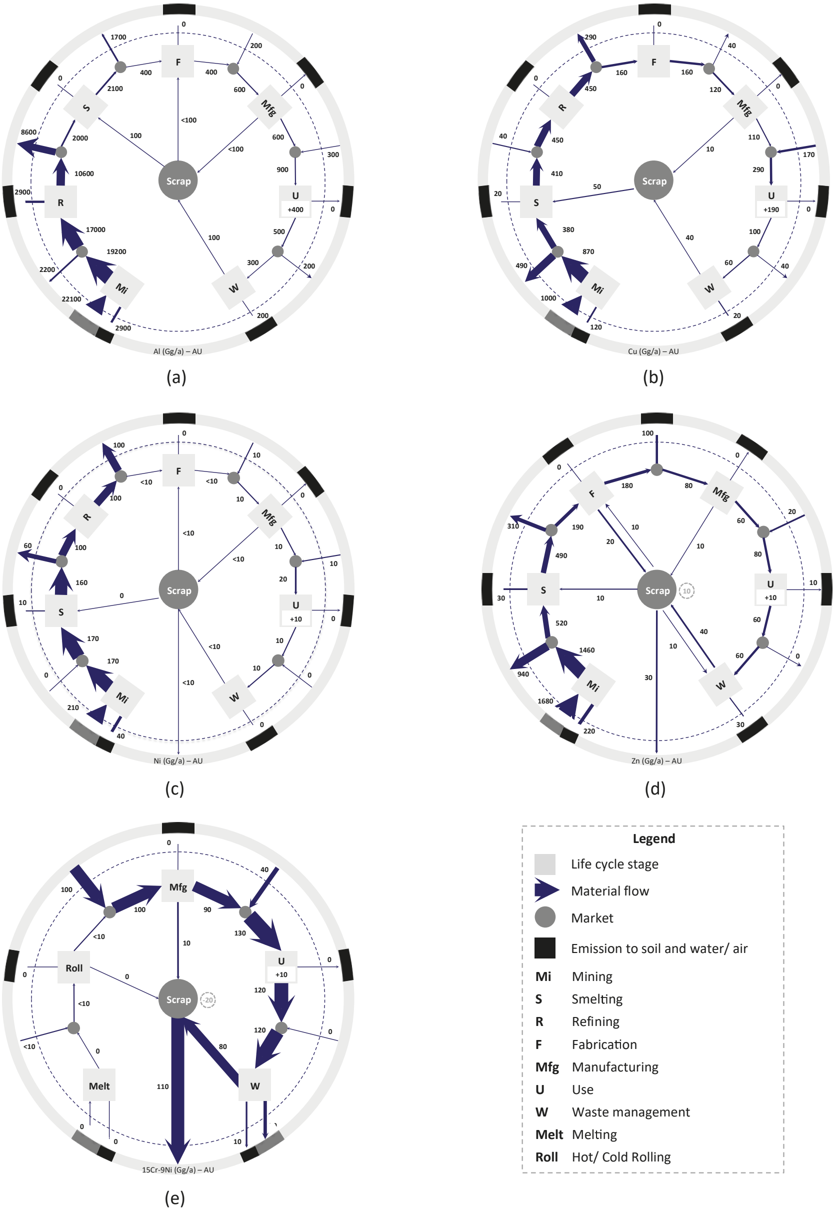

Figure 2. The Australian cycle of aluminum (**a**, this work), copper (**b**, this work), nickel (**c**, this work), zinc (**d**, [15]), and stainless steel 15Cr-9Ni (**e**, this work). The units are Gigagrams (thousand metric tons) of metallic equivalent per year. The year of reference is 2010. Flows may not add up due to rounding.

In Figure 3, the embodied energy in trade allocated to the targeted materials production is reported. Overall, greater embodied energy results in exports than imports for aluminum (90% and 15%, respectively), copper (96%, 43%), nickel (103%, 16%), and zinc (90%, 6%). In absolute terms, the cumulative results for the five materials follow those for aluminum, which is a main driver of energy embodied in trade for Australia due to the primary role of Australia in the global value chain of this metal and the relatively high energy requirements per unit of virgin aluminum processed. This trend becomes more evident if the embodied energy is compared to consumption (i.e., flow into use) rather than production (Figure 4). In this case, the energy embodied in exports of nickel and zinc is up to 8 times greater than that attributable to the amount of material consumed in Australia. For aluminum and copper, the energy embodied in exports is between 2 and 4 times that associated with the flow into use. For stainless steel 15Cr-9Ni, the entire flow into use in Australia is imported, with only a relatively small fraction of this alloy (5%) being exported in finished goods.

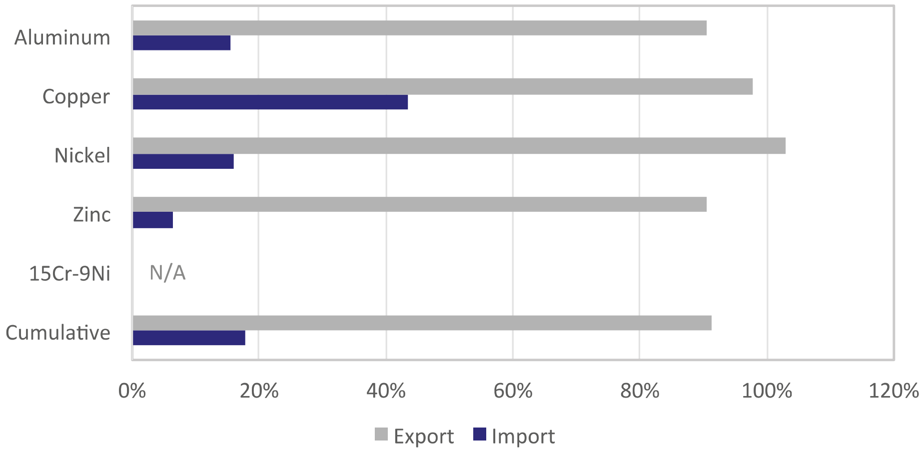

Figure 3. Energy embodied in trade as a fraction of metal production in Australia (%). N/A—Not applicable.

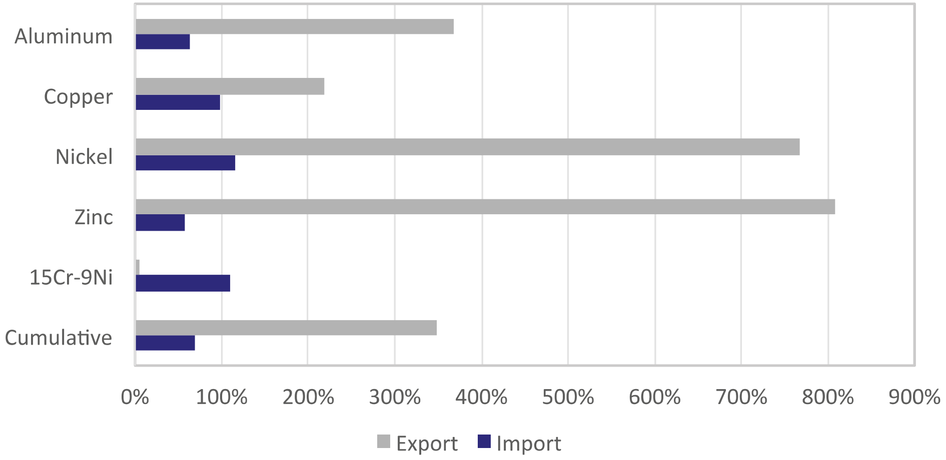

Figure 4. Energy embodied in trade as a fraction of metal consumption in Australia (%).

4. Discussion

Figure 2 makes it apparent that Australia is far from being a circular economy so far as metals and alloys are concerned. However, Lane [7] pointed out that the appropriate geographical scale for a circular economy is open to discussion. Within its national boundaries, Australia is active in the first stages of most metal life cycles, has a modest manufacturing capability, and possesses the potential for recovery and reuse at the end of product life [18]. That product life could be enhanced by designing for more efficient maintenance [19], refurbishment [20], remanufacture [21–23], and reuse, as well as cascading uses as an alternative to discard and improved separation [24]. Such actions would not help to circularize the Australian metals cycles, but would result in lowering the metal flow in imports to the use stage.

Australia has the potential for circular economy partnerships with countries around the world [25]. As pointed out above, however, each step of the process must make economic sense if it is to happen. Ultimately, increasing material circularity is one of the possible ways to improve the sustainability of resource use and to achieve the desired goal of extending the longevity of resources [26].

An innovative idea put forth by Giurco et al. [24] is that the rapid development of additive manufacturing may make it feasible for product manufacturing to be increasingly local—additive manufacturing could make it more efficient to produce new parts or products locally rather than to import them. The steps leading to additive manufacturing would be important to consider in this regard. To manufacture new products from discarded ones, the products would need to be disassembled in detail, the metal melted at perhaps 1000–1600 °C (depending on the metal), and the molten metal formed into powder by water or gas atomization [27] to enable additive manufacturing. This would add a step to the material's reuse process, and thus would need to make technological, energetic, and economic sense, but it might move some of Australia's metal cycles closer to circularization from a national perspective.

From the perspective of this paper, it is also of interest to ask "What is the prime motivating reason for supporting a more circular economy?" Among the possible answers to this question are (1) it will be economically beneficial, (2) it will minimize environmental impacts such as energy requirements and carbon emissions, and (3) it will conserve resources, especially scarce resources. Our discussion herein does not speak to the first of these, but it does address the last two. From that standpoint, an increasingly circular economy does indeed speak to resource conservation, but only if the scale of circularity is sufficiently broad.

The minimization of environmental impacts, supply risk, and vulnerability to supply restriction are features related to the global challenge of mitigating resource scarcity and are commonly covered in material criticality assessments [28]. The dynamic nature of criticality and its variance in space and among materials is influenced by geological, geopolitical, economic, social, technical, and regulatory factors [13]. For instance, Australia holds large deposits of major metals, but the global metal production network distributes material over a multi-tiered supply chain. While outsourcing and globalization may increase resilience to supply deficits, a diffuse and interlinked supply chain limits transparency and accountability, makes cascade-effects challenging to predict, and ultimately prevents the country from approaching or achieving material circularity [29].

This relationship and interdependence between organizations and the natural environment is a main source of complexity in the implementation of the circular economy [30]. Global awareness about the importance of integrating sustainability issues beyond the first-tier levels in supply chain management is increasing [31], but dispersed supply chains like those of minerals and metals are difficult to track within components and manufactured products originating from diverse sources [32].

As the metal cycles have demonstrated, Australia is a very significant supplier of primary resources to the rest of the world. This feature determines a shift between the location of metal production and that of use, which shapes national environmental profiles and may influence the perception of economic costs associated with global climate policy [33]. A considerable variation in energy requirements based on consumption (i.e., flow into use) rather than production introduces a geographical dimension in the environmental pressure of resource cycles and may reduce the net environmental benefits of recycling, ultimately undermining the potential to achieve carbon neutral economies.

At the national level, recovering an obsolete product containing, for instance, stainless steel (iron, chromium, and sometimes nickel and molybdenum) conserves the metals and/or alloys only if appropriate domestic processing technology exists. If it does not, the discarded material must be exported to an appropriate country or region where the technology resides, an action that might compromise both the environmental and economic aspects of resource recovery. The international trade of secondary materials and their recycling in countries with different CO_2-eq emissions per unit of electrical energy generated and different process efficiencies compared to those of primary producer countries may cause leakages in carbon accounting [33]. This is not to say that a circular economy goal is undesirable, but rather that it must be carefully analyzed in all aspects to make sure that its intentions can in fact be realized. Further refinement of the role of institutions and international trade in the circular economy concept is hence needed to solve the dichotomy between global efforts of policies, legislation, and society against individual company efforts of profitability, competitiveness, and manufacturing capacity [28].

5. Conclusions

In this work, the Australia anthropogenic cycles of five materials (four metals and one alloy) were analyzed and utilized to provide novel insights into the circular society potential for each of the cycles and carbon neutral prospects in Australia. Considering the role of Australia in the early stages of metal supply chains, the elemental information provided in this work will contribute to an understanding of the modern metabolism of the targeted resources as well as inform criticality assessments and scenario analyses. Absolute amounts of resources in metallic equivalents per life cycle stage were combined with related life cycle inventory per unit of mass of resource to estimate the gross energy requirements allocated to production, trade, and consumption for Australia. While the material flow approach can be used to highlight the magnitude of carbon emissions embodied in international trade, production-based emissions inventories may be preferable for demonstrating implications to global climate policy. More integrative research in this direction can build upon the framework demonstrated herein.

To summarize, the results in this work have demonstrated that a circular materials economy is difficult to impossible to achieve at the level of a single country. Australia has been used as an example, but no country anywhere has a complete collection of the technologies that would be needed in order to achieve circularity. It is apparent that a circular economy must be conceived at the global level, and must be cognizant of the losses that are inevitable at every life stage. In addition, the material handling and ocean transport needed for circularity need to be weighed against the potential environmental impacts of such activities. The circular economy concept remains a promising goal, but one that should not be slavishly followed to the detriment of other environmental goals.

Supplementary Materials: The following are available online at http://www.mdpi.com/2079-9276/8/1/32/s1, Table S1: Energy requirement per unit of aluminum processed. Values in MJ/kg Al, Table S2: Energy requirement per unit of copper processed. Values in MJ/kg Cu, Table S3: Energy requirement per unit of nickel processed. Values in MJ/kg Ni, Table S4: Energy requirement per unit of zinc processed. Values in MJ/kg Zn, Table S5: Energy requirement per unit of stainless steel 15Cr-9Ni processed. Values in MJ/kg 15Cr-9Ni.

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