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Editorial

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

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Received: 29 April 2020; Accepted: 25 May 2020; Published: 5 June 2020

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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.

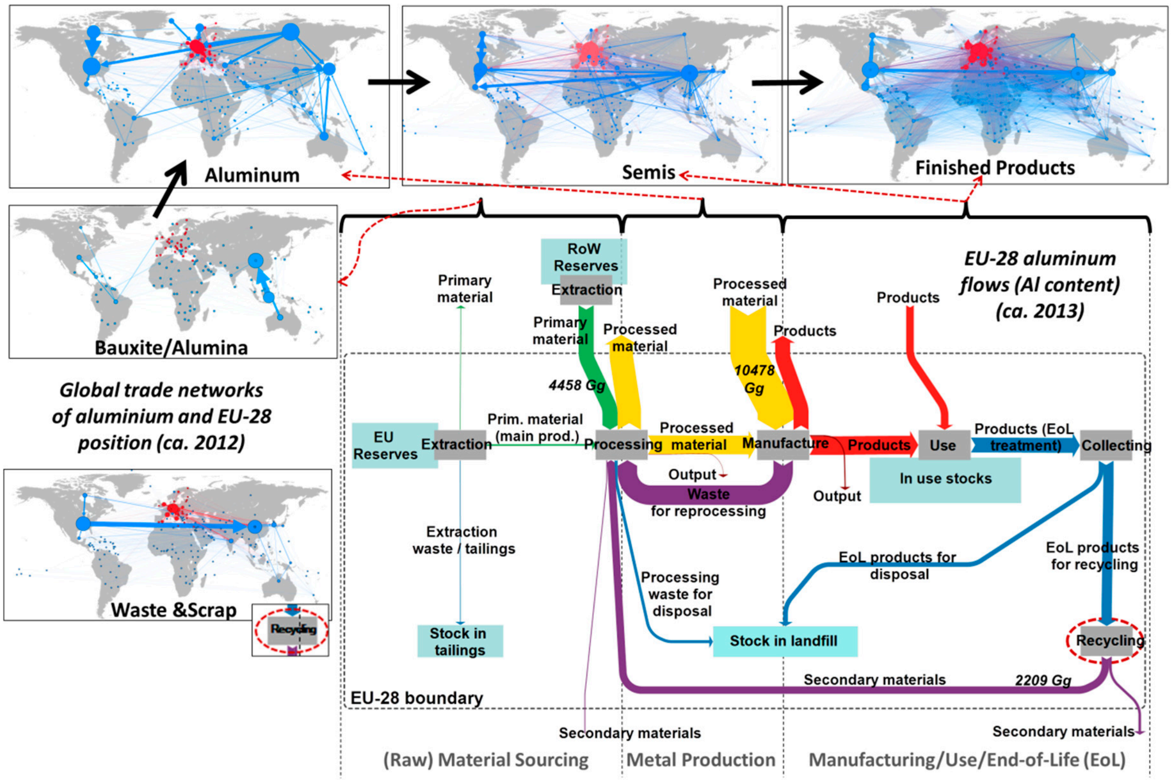

Figure 1. Schematic figure showing selected material flows (Sankey diagram) and the associated physical trade network of aluminum by life-cycle stage (physical trade flows are colored by source country, arrows are proportional to flow size, and node size is based on the sum of imports and exports) (Source: 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.

Author Contributions: L.M. and P.N. both equally contributed to writing this article and preparing the Special Issue. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: We thank the staff of MDPI Resources for their editorial support and the European Commission Joint Research Centre and Federal Environment Agency in Germany for their support in initiating this joint Special Issue.

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

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