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Addressing Sustainability Risks of Material is Key for a Just Energy and Industrial Transition – Research Directions from an Interdisciplinary View#

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ABSTRACT

Resources and raw materials are key enablers for the energy and industrial transformation needed to combat current climate and socio-ecological crises. Important substitution processes, such as defossilisation, shape the trajectory of the new raw material supply chain. Whenever raw materials or resources are sourced from the ground, processed, used and recycled, they can create unintended environmental, social and justice issues, leading to conflicting sustainability goals. Due to the complexity of interlinked effects, identifying and addressing these conflicts requires interdisciplinary collaboration. The aim of this paper is to propose sustainability risks of raw material supply as an innovative topic, explored from four different perspectives: (1) geo- and environmental science, 2) engineering, (3) economics and social science, and (4) material science, informed by sustainability science. As a method, we propose a five-step approach towards a comprehensive research agenda. Our approach establishes and builds on a common understanding of materials. As a result, we introduce three material categories, namely (1) *fossil energy resources*, (2) *base or mass materials*, (3) *critical raw materials* (step 1) and go through all five steps. Our results enable an extended understanding of sustainability risks of raw materials and resources, informed by relevant disciplinary aspects (step 2), normative insights from sustainability science (step3), and guiding questions for an expert assessment of blind spots and links to other disciplines and knowledge types (step 4). We discuss future research directions (step 5) and the need for accompanying research. In conclusion, an interdisciplinary approach is essential to understand sustainability risks of materials and resources and enable science to contribute meaningfully and help guide efforts to combat current socio-ecological crises.

Keywords: critical minerals, sustainable development, transition risks, supply risk, industrial transformation, energy transition

1. INTRODUCTION

Accelerating climate change and socio-ecological crises require fast implementation of climate and energy policies, as well as a fundamental change in how we produce, consume and live [1]. The related energy transition and industrial transformation is central to this process and at the heart of decision-makers', media and public discourses. In addition to sufficiency measures, innovative climate-friendly technologies are essential, and their development depends on specific resources, mineral and metal resources, most notably lithium, cobalt, copper and rare earth elements [2].

However, reliance on these resources across many technologies and areas of life creates major challenges for global supply and demand, as well as people and the planet. Demand for key raw materials is already rising and will continue to grow, while availability depends heavily on the size and distribution of geological deposits. This leads to a growing imbalance between global demand and limited regional supply. In addition to supply

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and demand issues, social, justice and environmental challenges arise, such as social conflicts. The situation is complicated by the lack of a shared interdisciplinary understanding of what defines a resource or material, and under which conditions a material is classified as critical.

Access to critical and limited raw materials raises pressing governance challenges: how can raw material supply and usage for the energy and industrial transition be secured while remaining aligned with climate targets and sustainability development goals? This issue is crucial because (i) insufficient availability of key raw materials risks slowing down the transition, (ii) the role of raw materials is still underrepresented in policy and academic debates, and (iii) existing governance initiatives largely emphasize supply security and competitiveness, often neglecting the full extent of socio-ecological impacts. Recent protests against a proposed lithium mine in Serbia's Jadar Valley show how opposition can extend beyond environmental risk to include cultural and community values [3].

The complexity poses a major challenge to the sustainable transformation of the energy and industrial system and can best be summarized under the topic "Sustainability risks of materials and resources". Sustainability risk has emerged as a key topic in the financial, banking, and insurance sectors, comprising so-called environmental, social, and governance sustainability risk. At present, the discourse predominantly focuses on climate-related transition and physical risks [4]. It shows that both neglecting sustainability concerns and fostering the transition towards more sustainability comes with risks, benefits and challenges that go beyond climate change related risk. These include justice and social aspects which are rather difficult to identify but important to consider. These observations resonate with the paper's main assumption. It underlines the need to expand the sustainability risk perspective beyond climate-related dimensions, providing a strong rationale for examining sustainability risks of materials and resource supply from an interdisciplinary viewpoint.

In response, this paper explores the "Sustainability risks of materials and resources" for the energy and industrial transition from an interdisciplinary perspective, integrating different research perspectives, such as (1) geo- and environmental science, 2) engineering, (3) economics and social science, and (4) material science, informed by sustainability science and guided by normative framework of the Sustainable Development Goals (SDGs). Our understanding of bringing these perspectives together is displayed in Figure 1.

As a central argument of this paper, we assume that, alongside the great value of disciplinary and techno-economic work, interdisciplinary approaches are necessary to address the topic in all its complexity. Our overall goal is to contribute to a deeper understanding of "Sustainability risks of materials and resources" in the context of sustainable development and propose future research directions. Insights from inter- and transdisciplinary fields, such as transformation and sustainability science,

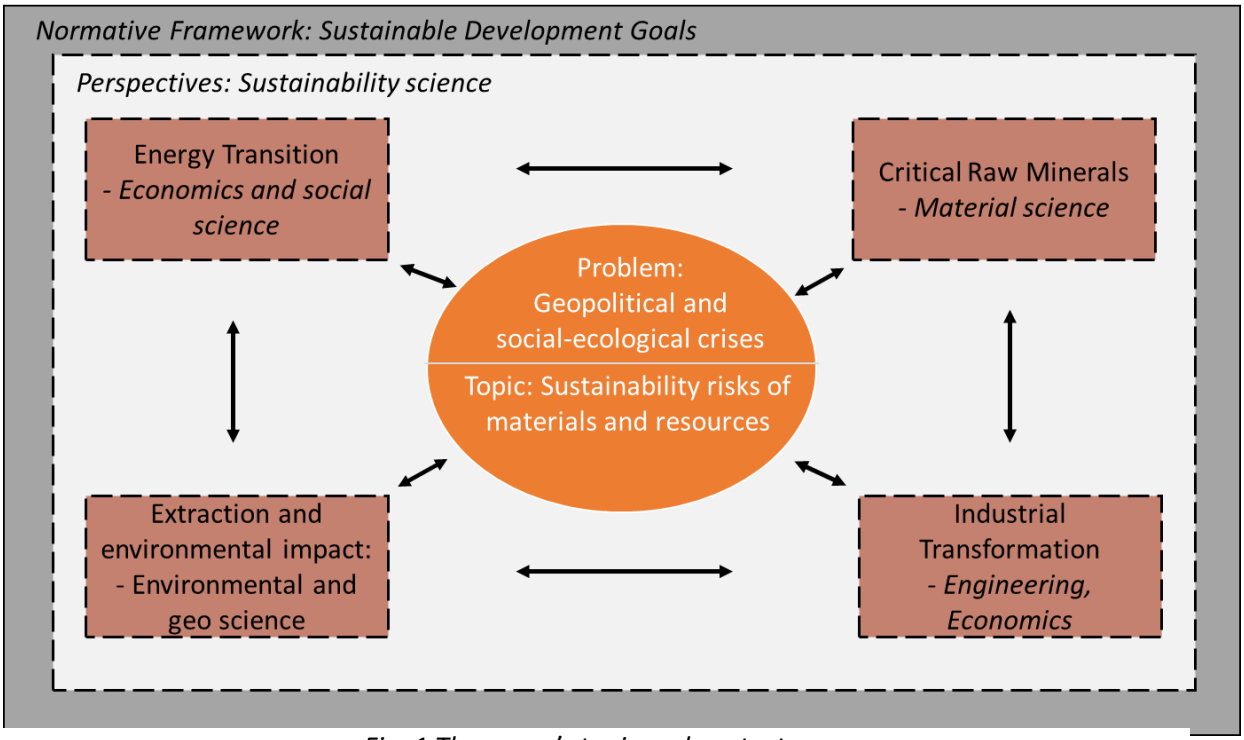

Fig. 1 The paper's topic and context.

alongside normative frameworks such as the SDGs, provide valuable guidance.

As a method, we propose and apply an approach which consists of five subsequent steps and enables a systemic exploration of the topics "Sustainability risks of material and resources" and supports the identification of innovative directions for future research. All five steps are applied throughout the paper. We introduce three material categories as a shared definitory foundation (step 1). Next, we identify relevant disciplinary (step 2) and normative aspects (step 3), and guiding questions for an expert-based assessment in form of a sustainability matrix (step 4). Based on these steps, we derive a structured research agenda that highlights promising disciplinary, inter-, and transdisciplinary research questions (step 5). Overall, the approach offers a transparent and transferable framework that can be adapted to other thematic contexts and supports more integrative sustainability-oriented research.

The novelty lies in the systematic integration of multiple disciplines that allow us to suggest three main material categories and future research directions to propose an innovative and underexplored rather new field: the sustainability risks of materials and resources. The paper is structured as follows: In the next section, we introduce our approach (section 2.1) and develop a shared definition of our topic (section 2.2). In section 3, we propose three material categories (section 3.1), identify relevant disciplinary (section 3.2) and normative aspects (section 3.3), which we bring together in our sustainability matrix (section 3.4). In section 4, we discuss future research directions and key insights. The paper ends with concluding remarks (section 5).

2. MATERIAL AND METHODS

2.1 The approach

In this paper we propose and apply an approach which consists of five steps. As shown in Figure 2, each of the five steps is linked to an outcome and result.

The approach begins with the development of a shared definition that distinguishes three material categories, namely (i) fossil energy resources, (ii) base and mass materials, (iii) critical raw materials (step 1) which we propose in section 3.1. In the second step, relevant disciplinary perspectives are identified, drawing on insights from geo- and environmental sciences, engineering, economics and social sciences, and material science (section 3.2). The third step integrates normative perspectives from sustainability science by considering different research types, forms of knowledge, and their relevance to the SDGs (section 3.3). Building on this foundation, the fourth step involves the development of a sustainability research matrix through an expert-based, question-guided evaluation (section 3.4). Finally, and as

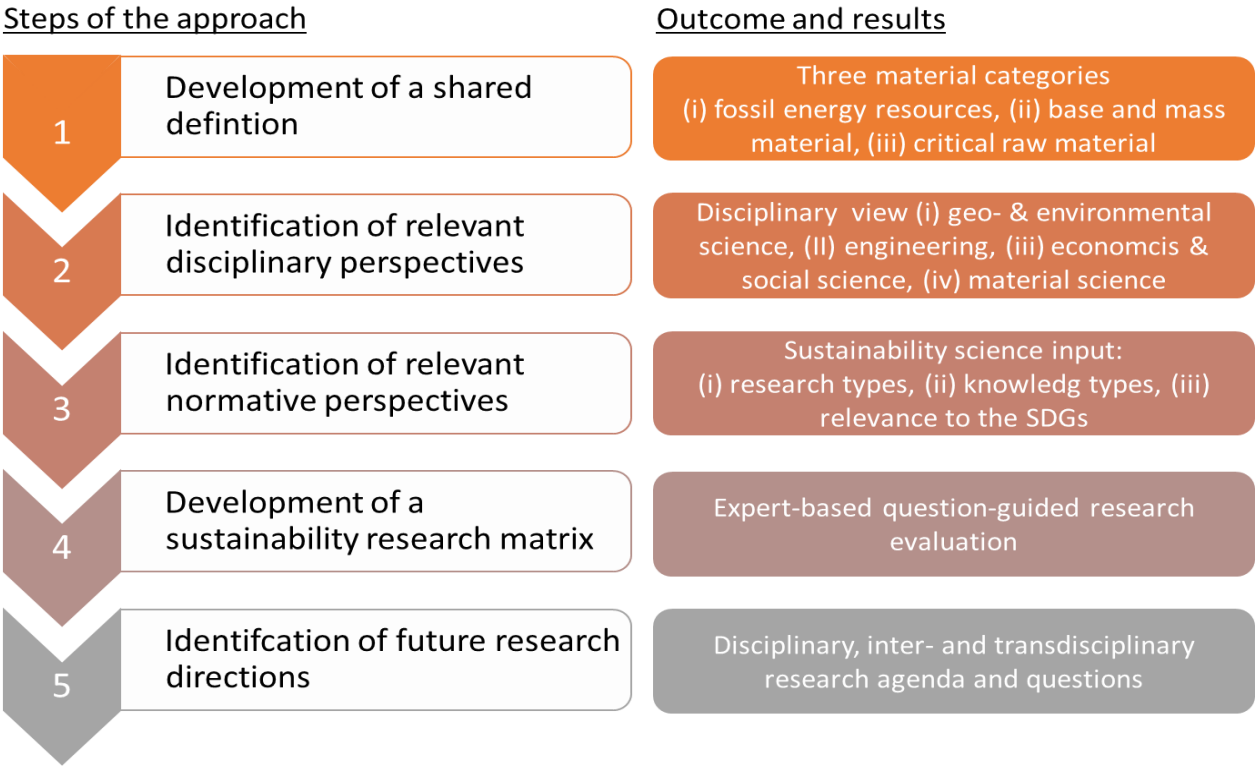

Fig. 2 The paper's five-step approach.

a main result, we discuss innovative future research directions by formulating a research agenda consisting of disciplinary, inter-, and transdisciplinary questions (section 4).

2.2 *The innovative topic "sustainability risk of materials and resources"*

To assess the complexity of the topic sustainability risk of materials and resources, it is useful to analytically differentiate its core components and examine how they interrelate across technical, societal, environmental and economic dimensions. The following four elements provide a basis for defining sustainability risks of materials and resources as an emerging and innovative sustainability research domain and serves as the study's foundation.

First, ***sustainability risks*** have increasingly gained relevance across financial, banking and regulatory domains. It comprises environmental, social and governance sustainability risk. These risks are typically defined as the potential negative impacts of environmental, social, and governance factors on economic performance, institutional stability, reputation, and societal well-being [5]. It refers to risk related to neglecting sustainability as well as risks that accompany the transition towards more sustainability. Current debates and regulatory frameworks predominantly focus on environmental risks, to be more precise on climate-related sustainability risks, particularly so-called transition risks arising from policy, technological, or market shifts and physical risks resulting from climate-induced extreme weather events such as heat waves or flooding (green swan: [4]. Climate-related fossil asset stranding, is a good example that combines the resource and sustainability risk topics and refers to the premature depreciation or value loss of an asset before its technical or anticipated lifetime [6,7]. However, this climate-focused perspective leaves other sustainability-relevant risk dimensions - such as environmental degradation beyond climate indicators, social inequality, governance deficits, and distributive justice concerns – so far comparatively underexplored.

Second***, materials and resources*** in the context of the sustainability transformation represent indispensable enablers of low emission and renewable energy, mobility, and industrial systems. Decarbonisation efforts rely heavily on a range of strategic minerals and metals, such as lithium and cobalt for battery and e-mobility technologies, and rare earth elements for permanent magnets used in wind turbines, hydrogen systems, and digital infrastructure. In recognition of this strategic importance, the European Union introduced the so-called Critical Raw Materials Act (CRMA) in 2024 [8]. The CRMA also seeks to strengthen resilient, diversified, and sustainable value chains spanning extraction, processing, recycling, and import diversification. Thereby they also aim at reducing structural dependencies and socio-ecological risk exposure and thus, strengthening the European economies' competitiveness.

Third, *the* ***sustainability risks of materials and resources*** in this study refers to the socio-ecological, technical, economic, and geopolitical risks emerging across the entire lifecycle of resource use. It ranges from exploration and extraction through processing, manufacturing, global trade, utilization, recycling and end-of-life management. These risks may manifest as social conflicts in mining regions, where workers lose their jobs such as in the German Ruhr-Area [9], labour exploitation, and hazardous working conditions in Gold mines in Congo [10], as well as environmental degradation through water depletion, toxic emissions, land-use change, and biodiversity loss. In economic and geopolitical terms, risks may include supply shortages, price volatility, trade disruptions, concentrated market power, and the intensification of global competition, potentially culminating in resource nationalism or resource-driven (armed) conflict. Importantly, these risks are both systemic and nonlinear, which means that they often produce cascading, cross-regional, cross-country and intergenerational consequences.

Fourth, the ***sustainability*** component underscores that these risks are not solely technical, market-related, or sector-specific challenges, but fundamentally embedded within global normative transformation agendas. The SDGs provide a guiding framework for identifying and addressing the sustainability risk of materials and resources. These risks are particularly relevant to SDG 7 (Affordable and Clean Energy), SDG 12 (Responsible Consumption and Production), SDG 3 (Good Health and Well-Being), and SDG 6 (Clean Water and Sanitation), as they directly influence the environmental and social conditions under which raw materials are extracted and processed. This demonstrates that material-related sustainability risks are closely linked to human health, resource efficiency, and access to clean energy and water. Accordingly, comprehensive risk assessment should go beyond narrow climate-financial perspectives and incorporate equity, distributional justice, planetary boundaries, and long-term socio-ecological integrity among others. This necessitates integrated, interdisciplinary, and transdisciplinary approaches that connect resource governance, socio-technical transition pathways, and SDG-oriented sustainability strategies.

In sum, the four analytical components highlight that sustainability risks of materials and resources constitutes an emerging sustainability research field situated at the intersection of multiple disciplines. Existing frameworks insufficiently address the multidimensional, complex, and interdependent nature of material-related sustainability risks, thereby revealing a conceptual and analytical blind spot in academic and policy debate. Building on this analytical topic analysis, the remainder of this paper develops an interdisciplinary understanding to deepen conceptual clarity, identify blind spots, and outline a future research agenda.

3. RESULTS

3.1 Developing a shared definition of materials

Our approach starts from the observation that sustainability risks of materials and resources arise from a growing imbalance between rapidly increasing demand for critical raw materials (as defined e.g. in the Critical Raw Materials Act) and limited, unevenly distributed supply. This imbalance creates and enhances socio-ecological crises such as ecological degradation from mining, social conflicts over land use, and risks of slowing down the energy and industrial transition.

We recognize that from a disciplinary perspective, usually only a specific part of the overall energy and industrial transition system is addressed. Consequently, there is no shared understanding of resources and materials and their specific role in the sustainability transformation [11]. Existing international and national assessments approach raw materials from distinct analytical perspectives. The International Resource Panel (IRP) primarily emphasizes material flows and associated environmental pressures, particularly for bulk and mass materials [12]. In contrast, EU's and OECD's analyses focus on economic importance and supply risks, forming the basis for the concept of critical raw materials [8,13,14]. National assessments by the German Federal Institute for Geosciences and Natural Resources (BGR) and related institutions such as the German Raw Materials Agency (DERA) further highlight supply-side vulnerabilities and processing-stage dependencies as is necessary for evaluating the national supply situations [15,16].

While these approaches provide robust insights within their respective domains, they remain largely disconnected across disciplinary boundaries and are typically addressed in isolation. This paper synthesizes these complementary perspectives by suggesting three categories of primary raw materials, namely *(1) fossil energy resources, (2) base or mass materials,* and *(3) critical raw materials*, as a structured framework for analyzing interdisciplinary sustainability risks of primary raw material supply:

- *Fossil energy resources,* mainly energy carriers that are burned, causing climate change. They have been in the center of geopolitical strategies for more than a century and linked to the "resource curse." Sustainability challenges related to this group are primarily governed through demand-side measures, such as fuel substitution and emission reduction policies, as the dominant environmental impacts arise during the use phase.
- *Base or mass materials*, such as steel, basic chemicals, minerals, cement, copper, and glass, many of which function as essential construction materials for buildings, infrastructure, machinery and appliances. While these materials are not rare, the sheer mass of their use creates substantial environmental burdens. In contrast to fossil energy resources, key sustainability challenges emerge predominantly during extraction and processing stages, where material- and energy-intensive transformations lead to high emissions and other environmental pressures. For example, processing from raw to basic materials is responsible for over 20 % of global GHG emissions [17].
- *Critical raw materials*, mostly minerals and metals needed in smaller amounts but with unique properties that enable technological innovations (e.g., renewable energy, semiconductor technologies), thereby supporting substitution of fossil fuels while also serving IT and defence sectors. For this group, sustainability concerns are closely linked to supply risks, geopolitical concentration, vulnerabilities along processing and refining stages and resilience of supply. Moreover, as material flows move from mine to refinery and traded products, the supply risk of base or mass materials can increase, potentially leading them to become critical as well [15].

3.2 Identification of relevant disciplinary perspectives

Raw materials and resources are framed differently across disciplines, yet all perspectives converge on their central role in energy and industrial transformation. In the following, we first outline widespread disciplinary perspectives on raw materials and resources in condensed overview form, always in the context of energy and industrial transformation.

Geo and environmental science perspective: In geosciences and mining engineering, minerals and metals are primarily framed as resources, with research focusing on exploration and extraction. Environmental and social impacts are addressed only to a limited extent, often technically - for example, improving mining efficiency - while the central focus remains on extraction itself. Broader perspectives, such as intrinsic value beyond utility, are rarely addressed. Ensuring raw material supply relies on efficient exploitation of geological deposits, including reuse of tailings, which contributes to resource savings. Nonetheless, mining is associated with significant environmental and social impacts worldwide, with no solution fully addressing these challenges.

Environmental engineering often uses life cycle assessment (LCA) to evaluate environmental impacts of mining and supply chains. LCA enables broad ecological evaluation and can include social and economic dimensions but remains quantitative and does not fully capture normative or ethical aspects of resource sustainability.

Material science perspective: In materials science, resources are elemental and compound inputs determining the chemistry, structure, processing, and performance of materials in industrial and energy systems. The core goal is to understand these properties to optimize design, production, and functionality. Traditionally, materials science emphasized deep disciplinary knowledge and performance optimization, largely neglecting social and environmental dimensions. Only recently have leading scientists begun addressing sustainability, considering environmental impacts of extraction, economic implications of eco-informed materials, and challenges of recycling complex materials.

Education, funding, and research priorities emphasize technical efficiency for applications in e.g., aerospace, energy, construction, and transport. The rise of renewable energy, electric mobility, and eco-conscious materials has shifted agendas toward integrating sustainability early in design. Seminal works by [18,19] provide systemic approaches for sustainable selection, production, recycling, and evaluation. Critical gaps remain, as recycling often leads to downcycling, primary extraction is emission-intensive, and substitution or re-mining potentials are underexplored. Bridging disciplinary expertise with sustainability science is essential to assess resource supply risks across material life cycles. Integrating environmental, social, and justice reduces fragility and supports sustainable energy and industrial transformation.

Economic and social science perspective: In economics, resources include human, financial, and natural inputs. Natural resources are renewable (e.g., water, wind) or non-renewable (e.g., minerals, oil), framed in terms of scarcity, allocation, and efficiency. Resource economics studies supply, demand, depletion, and environmental damage using tools like permits, taxes, and markets. Climate economics addresses externalities from fossil-based emissions. Ecological economics emphasizes biophysical limits, regeneration rates, and preservation of critical natural capital [20]. Resource curse and asset-stranding risks are increasingly studied in energy transition and development contexts [6,21]. Economics also considers renewable potential, fossil lock-ins, and energy security [22].

Traditional economics remains quantitative, often overlooking normative or political aspects. Heterodox schools—complexity, behavioral, and feminist economics—address social equity, justice, power relations, and networks. Scenario analysis integrates ecological, social, and economic dimensions, capturing uncertainties and informing sustainable resource use [23–25].

Engineering and technical science perspective: In engineering addressing energy and industrial transition, resources are defined from an energy-economics perspective, emphasizing economic value, utility, and efficiency. Resources include all known and estimated deposits; reserves are the economically and technically recoverable portion under current conditions. Reserves guide short-term planning; resources inform long-term supply security and investment decisions. The energy transition has a major impact on these decisions: in order to replace fossil fuels with renewable energy, metals and construction minerals are needed as primary metals for specific infrastructure. The main effect of the transition is therefore initially a shift in resource demand, not automatically a more sustainable use.

In that sense, technical sciences traditionally focus on improving efficiency, naturally intersecting with sustainability. Contributions include developing climate-friendly energy technologies, innovative bio-based materials, and circular economy approaches. Technical problem-solving alone does not account for socio-environmental impacts, such as community displacement or vulnerable populations. Integrating resource scarcity, environmental consequences, and social responsibility into technology design is essential for sustainable and resilient energy and industrial transition [26,27].

Taken together, these disciplinary perspectives highlight both complementarities and blind spots. Bridging them with sustainability science is crucial to address

risks, trade-offs and potential synergies of raw material supply in the energy and industrial transformation

3.3 *Identification of relevant normative perspectives*

In this section, central elements from sustainability science, transformation and SDG research are distilled to move the topic beyond disciplinary boundaries toward a holistic assessment in the sense of a just transition.

Sustainability and transformation study scholars identify three types of knowledge needed for just transition [28,29]. System knowledge refers to understanding the structure and dynamics of the problematic status quo, such as the interlinkages between ecological and social dimension of resources. Target knowledge provides normative orientation toward desirable futures, acknowledging, for example, that ongoing poly-crises are the new normal and that a desirable future for sustainable use of critical resources can be actively designed. Transformation knowledge considers pathways and strategies to reach these futures, addressing ethical dimensions of socio-ecological crises and fostering interdisciplinary and transdisciplinary ex-change.

In the context of the paper, these knowledge types offer a valuable framework for identifying new topical pathways and forms of knowledge needed to study sustainability risks of resource supply in a holistic way. It encourages considering normativity, when it comes to desired future, and helps to identify blind spots of knowledge, mainly in the categories transformation knowledge" and "target knowledge".

Furthermore, sustainability and transformation scholars distinguish between different types of research conducting. Traditional research focuses on knowledge production and is problem- and output-oriented within a linear science-policy model, mostly maintaining disciplinary boundaries. Transformation research conducts research about the transformation. It aims to understand the change process, has an input-oriented science-policy relationship providing scientifically based impulse for change. Transformative research goes further and conducts research for transformation, actively seeking to contribute through participatory co-creation with societal actors, using a transdisciplinary and dialogical science-policy approach [29,30].

For the paper, the three types of knowledge production call for courage to explore new research paths and provide methodological guidance. Applying this typology offers distinct lenses for examining sustainability risks of resource supply. While traditional approaches are valuable for understanding the problem itself, additional forms are needed. Transformation research deepens the understanding of dynamic processes – such as technological, geopolitical, or societal shifts – and might benefit from scenario analysis. Actively shaping the issue in real-world contexts requires involving stakeholders through participatory formats, such as developing a new index.

The 17 SDG provide a normative and integrative framework for assessing sustainability goals and conflicts, which can be applied to critical resource supply in the context of energy and industrial transformation [31]. Especially SDG 7 (Affordable and Clean Energy), SDG 12 (Responsible Consumption and Production) and SDG 8 (Decent Work and Economic Growth) seem relevant for the topic of critical resource supply. For example, SDG 7 is crucial, as the transition to renewable energy and low-carbon industrial systems depends on critical resources such as lithium, cobalt, and copper. Supply constraints of these materials can directly hinder access to clean energy and lead it increasing prices, which is problematic from a social perspective. SDG 12 emphasizes efficient, sufficient and consistent use of materials and resources, minimizing environmental impacts, and promoting circularity in industrial processes. From the perspective of materials science and engineering, it guides research on efficient material use, recycling, and lifecycle assessment. Geo- and environmental sciences use it to evaluate extraction methods and ecological impacts of mining and resource processing. Economics and social sciences apply SDG 12 to analyze equity, resource governance, and distribution-al consequences of industrial and energy transformations

Considering the SDGs for the topic of sustainability risks of resource supply is a promising step toward greater normativity, embracing real-world complexing, as it considers desired goals and identifies related conflicts, and shows that bringing together different disciplinary perspectives is essential. Linking these goals to policy dimensions further enables actionable strategies and helps align research with societal needs.

In a nutshell, SDGs, the different types of knowledge and research conduct provide valuable guidance and inspiration to move beyond siloed analysis and open new pathways for inter- and transdisciplinary research on critical resources, while valuable disciplinary research. Central elements from sustainability science, transformation studies, and SDG research guide a more holistic assessment of sustainability risks in raw material supply.

3.4 *Developing a sustainability research matrix*

Step four of our approach consists of the development of a sustainability research matrix for the topic of

sustainability risk of materials and resources. The aim to do so is twofold.

First, we aim to provide a comprehensive overview of how different disciplines relate to and can be classified according to three key aspects: (1) SDGs, (2) knowledge types, and (3) research types. In doing so, the matrix fosters mutual understanding and appreciation of the disciplinary contributions to sustainability research. Second, the matrix serves as the basis to map four core research perspectives in relation to the three materials categories. It highlights not only the specific focus areas of each discipline but also their intersections and areas of overlap.

Building on this foundation, the analysis allows for the identification of disciplinary strengths, potential avenues for collaboration, and emerging research questions at the interfaces between disciplines. It thus contributes to the advancement of integrative sustainability research.

To inform the development of the matrix, our disciplinary experts, who also serve as the contributing authors, were invited to respond to the following guiding questions:

- **Knowledge types:** Based on your experience, what types of knowledge are most commonly prioritized within your discipline?
- **Research types:** Regarding different types of research (e.g., basic, applied, transformative), where would you locate the main focus of your discipline from your professional perspective?
- **Sustainable development:** Which research topics within your field address the SDGs and broader sustainability issues?
- **Interdisciplinary overlaps:** Where do you see intersections or points of overlap between the topics mentioned in your discipline and those of other disciplines?

These four questions are answered with reference to the three material categories as defined in Section 3.1, and in relation to the overarching topic of sustainability risks of materials and resources. While this study focuses more on proposing the matrix, its full assessment will be part of our future research.

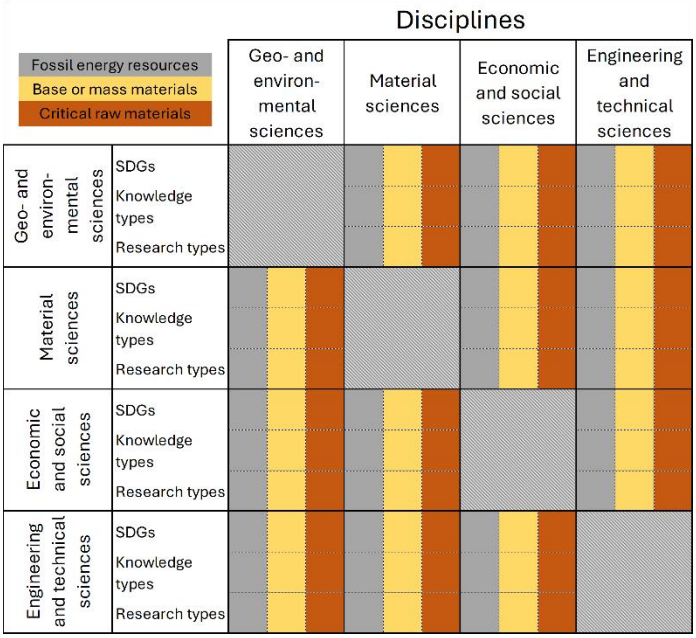

Fig. 3: Template for the sustainability research matrix.

4. DISCUSSION

This section outlines possible research directions on the sustainability risks of materials and resources, representing a first step toward a comprehensive agenda. Building on Sections 2.1–2.4, we identify four overarching, interdisciplinary research questions:

1. How can critical raw material and base material extraction and supply be aligned with a broadened understanding of sustainability, integrating environmental, socio-cultural, and justice dimensions?
2. What scenarios and pathways ensure sufficient critical raw material supply for the energy and industrial transformation while minimizing socio-ecological risks and trade-offs across supply chains and ideally creating synergies?
3. Which governance and policy frameworks can balance critical raw material and base material security with sustainability goals, and how can indicators or risk indices support such decision-making?
4. Which material substitutions and transformative shifts in processing or product design can lead to the most effective reductions in terms of sustainability risks, and synergies in the context of a just transition [32]?

Additionally, accompanying research from sustainability science as a science-of-science case study on interdisciplinary cooperation seems valuable [33] and might comprise the following two key questions:

1. How can inter- and transdisciplinary research on and for sustainability be institutionalized at the university level, where research is mainly conducted within disciplinary silos?
2. How can learning processes at the individual researcher level be enabled to go beyond disciplinary comfort zones?

From our analysis, three key insights emerge. First, new indicators or a comprehensive sustainability risks index are needed to systematically compare risks across raw materials, regions, and supply chain stages, supporting informed decision-making. Second, SDG conflicts and trade-offs vs. synergies arise as a central issue, requiring a shared anchor point and interdisciplinary integration. Third, understanding trade-offs and synergies across scales – from local impacts to global demand – remains a major challenge for future research.

Additionally, five collaboration learnings complement these content insights. First, disciplines vary in their familiarity with interdisciplinary frameworks such as SDGs or research types, which require active translation between fields. Second, defining common concepts fosters collaboration by bridging barriers between disciplinary languages and revealing blind spots. Third, the diversity of included disciplines proves valuable, as it covers the full value chain across local, regional, and global levels. Fourth, sustainability science add social and justice dimensions that connect all perspectives, helping to achieve a holistic view. Finally, beyond the paper's core research perspective, it seems necessary to include further perspectives such as business controlling and value chain analysis, or industrial ecology perspective.

5. CONCLUSIONS

The aim of this paper was to introduce the sustainability risks of materials and resources as an innovative topic and to propose future research directions. To do so, we proposed a five-step approach and proposed three material categories (1) fossil energy resources, (2) base or mass materials, (3) critical raw materials (step 1), and identified relevant disciplinary (step 2) and normative aspects (step 3). Step 4 comprises a question -guided sustainability matrix that allows us to assess disciplinary blind spots and interlinkages with other disciplines, SDGs as well as different research types and knowledge types.

In sum, advancing research on sustainability risks of materials and resources requires an interdisciplinary approach informed by normative frameworks that transcend disciplinary boundaries. Such an integrative view is not only crucial for informed decision-makers, but also for fostering a just and renewable future within planetary boundaries.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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