TIME MATTERS.

Unlocking the transformative potential of strategic approaches towards a more sustainable metal use

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“The future is not some place we are going, but one we are creating. The paths are not to be found, but made. And the activity of making them changes both the maker and the destination.”

— John H. Schaar

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Summary

Achieving the 'Great Transformation' demands a closer consideration of the material basis of technologies, whose broad-scale implementation is often associated with efficiency improvements and progress towards a post-fossil society, but which is largely disregarded as of today. At the same time, the discourse on resource-related issues only rarely evolves around achieving an actual fundamental shift towards sustainability in the sense of a 'material transition'. The notion of this mutual disconnect – a 'transformation-material gap' that exists in both research and practice – is the main driver for this dissertation.

Metals fulfill crucial functions in areas as diverse as renewable energy, digitization and life style appliances such as smart home concepts, mobility, communication, or medicine. In the context of sustainability, achieving a more sustainable metal use means (i) minimizing the adverse effects associated with metal production and use and (ii) sustaining the availability of metals in a way that benefits present and future generations. Urgent need to act to avoid bottlenecks as well as meeting the challenge of possible conflicts of use among those areas of application calls for appropriate strategy making to intervene in the complex field of metal production and use that involves various, often interlinked operating levels, actors, and spatial and temporal scales.

Located within the field of sustainability science, this dissertation focuses on strategies as a means to intervene in a system. It pursues the question, which design features could guide future strategy making to foster sustainability along the whole metal life cycle, and especially, how a better understanding of temporalities – i.e. understanding time in a diverse sense – could improve strategy design and help to bridge the assumed 'transformation-material gap'.

My research converges the results from four research studies. A conceptual part explores the role of temporalities for interventions in complex and interlinked systems, which adds to the conceptual basis, on which the empirical part builds up to explore present and future interventions in metal production and use. The research revealed three essential needs that future strategies must tackle: (i) managing the complex interlinkages of processes and activities on various operational levels and spatial and temporal scales, (ii) providing clear guidance concerning the operationalization of sustainability principles, and (iii) keeping activities within the planet's carrying capacity and embracing constant change as an inherent system characteristic.

In response to these needs, I developed three guidelines with two design features each (one relating to content, and one to the process of formulating and implementing the strategy) to guide future strategy making:

1. Design strategies based on a profound understanding of the system and its interrelations, but bear in mind context-specific characteristics. *(Comprehensive, but tailored.)*
2. Design strategies to achieve fundamental change in a cooperative and inclusive manner. *(Ambitious, but manageable.)*
3. Design strategies to strengthen resilience in a constantly changing environment. *(Dynamic, but consistent.)*

My results show that TIME MATTERS in this respect. If considered in close relation to space and diversely understood in the sense of temporalities, it serves to (i) understand the impact (duration and magnitude) of an intervention, (ii) recognize patterns of change that go beyond establishing linear, one-dimensional connections, and (iii) design interventions in a way that considers the resilience of a system.

While these findings can contribute to closer considering our understanding of transformation processes towards sustainability in future interventions in metal production and use, more research is needed on approaches that bring the material basis into closer consideration of transformation processes in research and practice.

Zusammenfassung

Ein Gelingen der 'Großen Transformation' erfordert eine genaue Berücksichtigung der Ressourcenbasis für diejenigen Technologien, deren Einsatz häufig mit einer verbesserten Effizienz und dem Fortschritt in Richtung einer post-fossilen Zukunft assoziiert wird, die aber heute noch oftmals übersehen wird. Gleichzeitig behandelt der Diskurs zu rohstoffrelevanten Themen nur selten einen tatsächlichen fundamentalen Wandel in Richtung Nachhaltigkeit im Sinne einer ‚Stoffwende'. Es ist vor allem diese Vorstellung einer gegenseitigen Verbindungslosigkeit – eine ‚Transformations-Stoff-Lücke' (‚transformation-material gap') –, die diese Dissertation antreibt. Metalle erfüllen entscheidende Funktionen in Anwendungsbereichen, die von der Nutzung erneuerbarer Energien über Digitalisierung und Lifestyle-Anwendungen wie Smart Home-Konzepte, bis hin zu Mobilität, Kommunikation oder Medizin reichen. Im Nachhaltigkeitskontext bedeutet das Erreichen eines nachhaltigeren Umgangs mit Metallen (i) ein Minimieren der negativen Auswirkungen, die mit der Metallgewinnung und ihrer Nutzung einhergehen und (ii) eine Sicherstellung der Verfügbarkeit von Metallen in einer Weise, die heutigen und zukünftigen Generationen zugutekommt. Dringender Handlungsbedarf mit Blick auf die Vermeidung von Versorgungsengpässen sowie die Notwendigkeit, Nutzungskonkurrenzen zwischen den verschiedenen Anwendungsbereichen zu begegnen, erfordern die Formulierung und Umsetzung von Strategien, die der Komplexität des Systems der Metallgewinnung und -nutzung, das unterschiedlichste Handlungsebenen und Akteure sowie räumliche und zeitliche Skalen einbezieht, adäquat Rechnung tragen.
Angesiedelt in der Nachhaltigkeitsforschung konzentriert sich diese Dissertation auf Strategien als ein mögliches Mittel, lenkend in Systeme einzugreifen. Sie verfolgt die Frage, an welchen Design-Merkmalen künftige Strategie-Prozesse sich orientieren können, um Nachhaltigkeit entlang des gesamten Lebenszyklus' zu fördern. Insbesondere geht sie der Frage nach, wie ein vertieftes Verständnis von Zeitlichkeit *(temporalities)* – also ein vielfältigeres Verständnis von Zeit – Strategien verbessern und zu einer Schließung der oben beschriebenen Lücke zwischen Transformation und Metallgewinnung und -nutzung beitragen könnte.
Meine Forschung bringt die Ergebnisse aus vier unterschiedlichen Studien zusammen. Ein konzeptioneller Teil erkundet darin die Bedeutung von Zeitlichkeit und zeitlicher Vielfalt für Eingriffe in komplexe und zusammenhängende Systeme, und trägt so zur konzeptionellen Basis bei, auf der ein empirischer Teil aufbaut, der gegenwärtige und künftige Eingriffsmöglichkeiten untersucht. Dabei zeigt sich, dass Strategien vor allem auf drei Bedürfnisse zu reagieren haben:

(i) einen Umgang mit den komplexen Zusammenhängen unterschiedlicher Prozesse auf den verschiedenen einschlägigen Handlungsebenen und Skalen finden, (ii) eine klare Orientierung für die Operationalisierung von Nachhaltigkeitsprinzipien bieten, und (iii) sicherstellen, dass Handlungen mit der Tragfähigkeit des Planeten im Einklang stehen und kontinuierlichen Wandel als system-inhärent begreifen.

Als Antwort darauf wurden drei Richtlinien formuliert, aus denen wiederum jeweils zwei Design-Merkmale resultieren: Eines, das sich auf den Inhalt der Strategien bezieht und eines, in dem es um Aspekte der Formulierung und Umsetzung der vorgeschlagenen Maßnahmen geht:

1. Formuliere Strategien basierend auf einem vertieften Verständnis für das betreffende System und dessen Zusammenhänge, aber beachte dabei kontextspezifische Besonderheiten. *(Umfassend, aber maßgeschneidert.)*
2. Formuliere Strategien mit dem Ziel, tiefgreifenden Wandel (auch) mithilfe eines kooperativen und inklusiven Ansatzes zu erreichen. *(Ehrgeizig, aber umsetzbar.)*
3. Formuliere Strategien in einer Weise, die die Resilienz des Systems auch unter sich stetig wandelnden Bedingungen stärkt. *(Dynamisch, aber konsistent.)*

Die Ergebnisse der vorgestellten Forschung zeigen, dass Zeit hier von entscheidender Bedeutung ist (‚TIME MATTERS'). Solange sie gemeinsam mit räumlichen Skalen und im Sinne zeitlicher Vielfalt betrachtet wird, trägt Zeit dazu bei, (i) die Wirkung (Dauer und Stärke) eines Eingriffs besser abzuschätzen, (ii) Muster des Wandels über rein lineare oder eindimensionale Verbindungen hinaus zu erkennen, und (iii) Eingriffe so zu gestalten, dass sie die Resilienz eines Systems berücksichtigen.

Während diese Ergebnisse dazu beitragen können, unser Verständnis von Transformationsprozessen in Richtung Nachhaltigkeit besser in unseren Umgang mit Metallen einfließen zu lassen, besteht weiterer Forschungs- und Handlungsbedarf hinsichtlich Ansätzen, die eine stärkere Berücksichtigung und Anerkennung der stofflichen Basis von und in Transformationenprozessen fördern.

1 INTRODUCTION

1 Introduction

Sometime during 2016, humanity reached the point, where – statistically – each inhabitant of this planet had a little more than one mobile phone in active use (ITU, 2017). Smartphones are now increasingly applied in "smart home" concepts to improve energy management in private households (Belkhir and Elmeligi, 2018). More than 36,000 electric vehicles were newly registered in Germany in 2018 (statista, 2018), and 2017 saw another 5,300 megawatts of on-shore wind power capacity added to the already existing facilities (Internationales Wirtschaftsforum Regenerative Energien (IWR), 2018).

These developments exemplify processes that are currently on-going as the beginning or part of the "Great Transformation" (WBGU, 2011) towards a more sustainable society that tackles the challenges of a changing climate on the path towards a post-fossil age. In the public discourse, they are usually considered as indicators for innovation and progress towards sustainability and might, in the light of improved resource efficiency, even be associated with dematerialization trends in the economy (Steinberger et al., 2010). Expressions such as storing data 'in the cloud', the 'digitization of industrial processes' on the path towards an industry 4.0, and 'digital medicine' that is one of the pillars of Germany's high-tech strategy for 2025 (BMBF, 2018) are just few of many examples to illustrate how these innovation processes are largely perceived and communicated. Such notion, however, not only disregards the increasing share of the information and communication industry to global greenhouse gas emissions (Belkhir and Elmeligi, 2018), but fails to consider one very vital issue: A broad implementation of these innovations requires a large material basis. Metals in particular are of importance here (Exner et al., 2016a; Schindler, 2016). This material basis, that is a prerequisite for achieving a variety of other transformation processes such as the energy transition or digitization processes such as those described above, is largely underrepresented in the consideration of societal transformation processes to date. At the same time, the discourse on resource-related issues such as more sustainable mining or innovative metal recycling technologies only rarely relates to such societal transformation processes or evolves around achieving an actual fundamental shift towards sustainability in the sense of a 'material transition'. The notion of this mutual disconnect – a 'transformation-material' gap that exists in both research and practice – is the main driver for this dissertation.

I postulate that in order to achieve a more sustainable metal production and use[1] closing this gap will be of vital importance. Achieving the necessary fundamental shift in our patterns of metal production and use requires a profound and practically applicable understanding of transformation processes; and achieving the Great Transformation towards sustainability strongly requires an appropriate material basis and thus calls for a profound understanding of the interlinkages of current patterns of metal production and use. Interventions in this system, often subsumed as issues of 'resource governance' (Ali et al., 2017; Bleischwitz and Bringezu, 2008; Prior et al., 2013), that aim to achieve such change, need a clear strategic orientation and must be designed in a way that bridges the existing gap between transformation processes and patterns of metal production and use. Existing strategic approaches are difficult to compare and assess due to their different foci (such as on single life cycle phases, on mineral resources in general or on critical metals in particular) as well as their application in varying contexts and on different operational levels (such as companies, nations, or non-governmental organizations (NGOs)). Consequently, their potential contribution to achieving the desired material transition remains unclear.

Increasingly, research acknowledges the need to consider the temporal implications of such fundamental change processes (Patterson et al., 2017; van der Leeuw et al., 2012). Most of these approaches, however, consider time only in the sense of 'clock time', establishing linear, one-dimensional connections between the present and the future (Held, 2001). According to my hypothesis, a diverse consideration of temporal aspects, that also considers other temporalities like rhythms and specific patterns of change, would not only support informed decision-making and improve strategic approaches. It could also contribute to drawing connections between the largely unlinked fields (in research and practice) that deal with transformation processes and processes of metal production and use.

Therefore, this dissertation focuses on strategies as a means to intervene in a system that can incorporate a variety of temporalities, and pursues the following over-arching research question:

[1] For the purposes of this dissertation, the expression *metal production and use* refers to the complex of processes along the metal life cycle including extraction, concentration and purification, transport, product design, use and End-of-Life (EoL) treatment and recycling (Hagelüken and Meskers, 2010; Kümmerer and Clark, 2016; van Berkel, 2007). It considers that metals should be used rather than consumed, emphasizing the need to minimize dissipation along the life cycle (Exner et al., 2016b).

What are design features of strategies that contribute to achieving the transformation towards more sustainable metal production and use, and how could a better understanding of temporalities improve strategy design?

Fig. 1 illustrates the conceptual frame of the dissertation. My research centers on the intersection of sustainability, transformation and metal production and use (*illustrated as bubbles*) and explores diverse temporalities (*the blue triangle*) as a connecting element concerning strategic interventions in a system (*grey center*). The concept of sustainability serves as 'research lens' and guiding normative concept that is embedded in sustainability science. The (scientific) discourse on transformation processes forms the conceptual research background and embeds the dissertation in the larger context of transformation research. Processes of metal production and use are the main research object and frame the scope of the presented research (in the sense of a 'boundary object' (Star and Griesemer, 1989)), embedded in the larger research context on sustainable resource governance.

My **main research contribution** is thus to advance the discourse on sustainable resource governance by *contributing to the enhancement of strategic approaches* to intervene in metal production and use through a closer and more connected consideration of temporal diversity and transformation processes towards sustainability.

These research insights shall then also inform

- the *scientific discourse on transformation processes* through a more distinct understanding of interventions in a system to affect intended, fundamental change, especially through the consideration of temporalities, and
- *sustainability research* regarding the potential of strategic approaches to intervene in complex systems towards meeting the challenges associated with metal production and use.

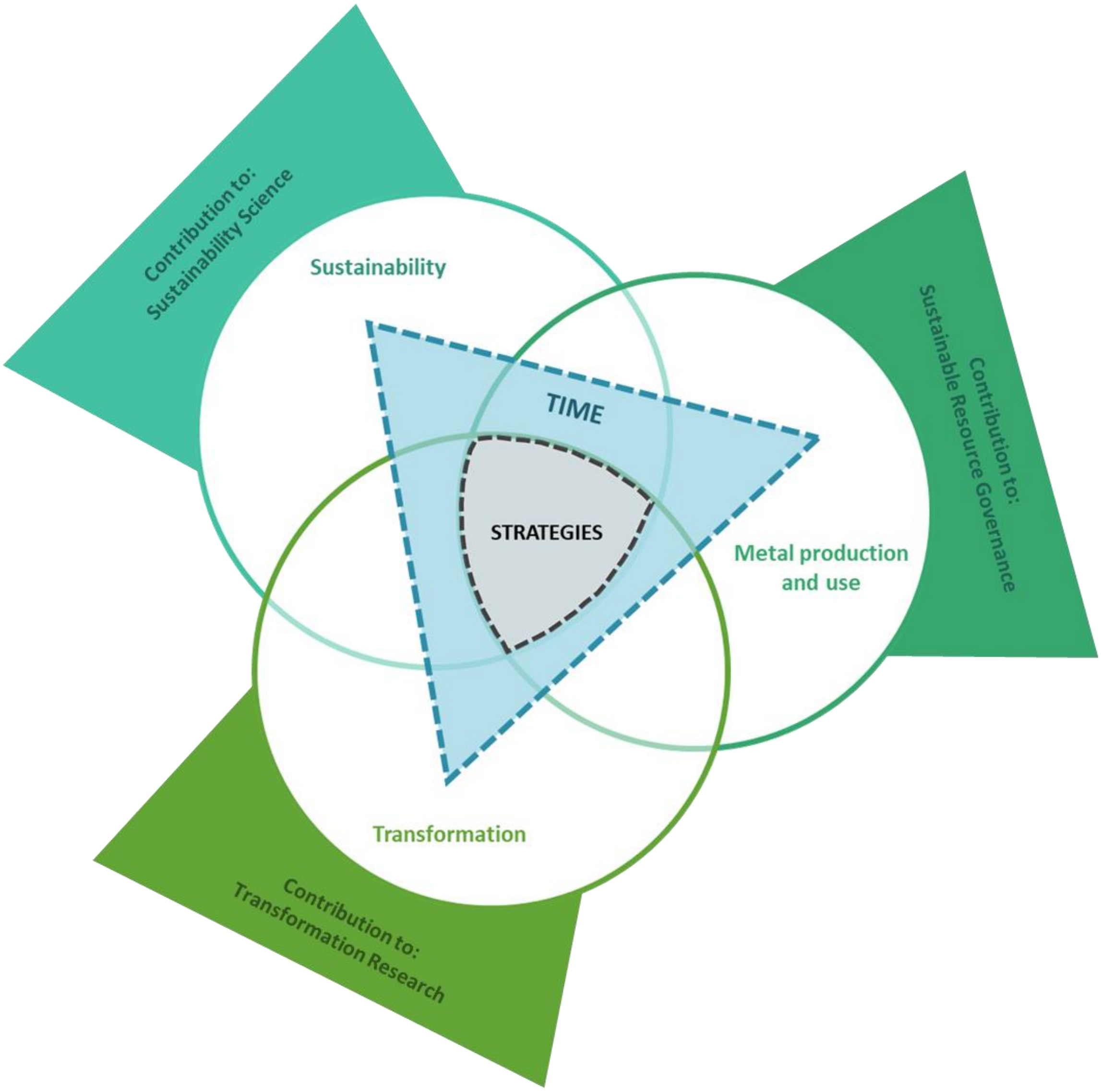

Fig. 1: The main themes and conceptual frame of this dissertation

The dissertation is structured as follows (compare Fig. 2): In chapter 2, I introduce the relevant research background, referring to the conceptual frame (Fig. 1). In chapter 3, I present the overall research design to fill the identified research gaps and illustrate the connections between the four research articles that form the core of this cumulative dissertation. These studies are presented in the results section (chapter 4). As indicated in Fig. 2 and further elaborated in chapter 3, the results have a conceptual and an empirical part, whereof each delivers a specific perspective on the research issue. The synthesis (chapter 5) consists of two parts that aim to bring the results together (i) from the perspective of strategy design and (ii) from the perspective of the larger research context (transformation and sustainability research). I conclude in chapter 6 with a summary of my findings and implications for further research.

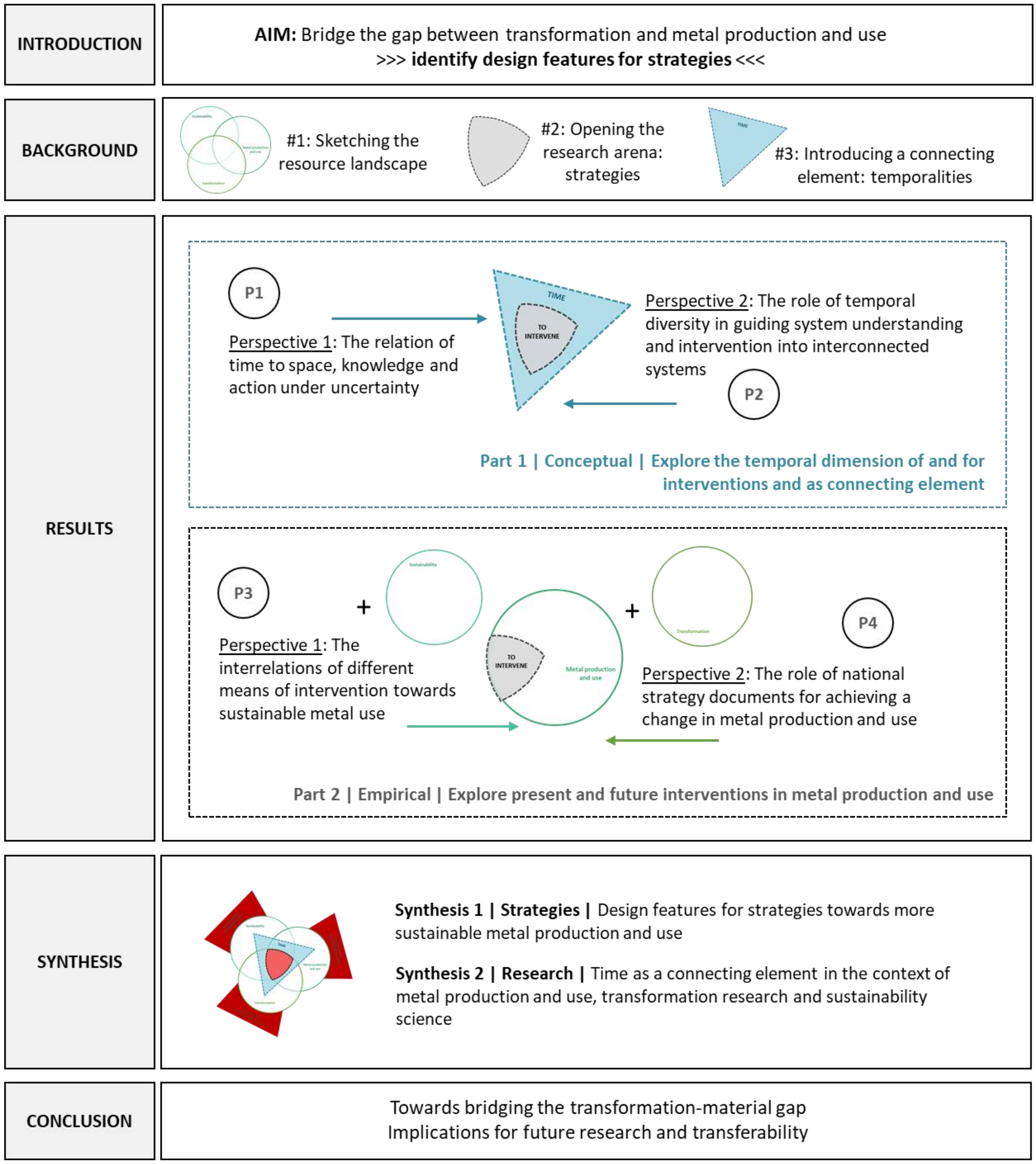

Fig. 2: Structure of the dissertation

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2 BACKGROUND

2 Background

Referring to Fig. 1, I am here introducing the state of research relevant for this dissertation. I will refer first to the broader research landscape concerning sustainability, transformation and metal production and use, in which this dissertation is embedded. Then I turn to the focus of my research ('research arena'), which is in analyzing the possible contribution of strategies as an approach to intervening in metal production and use. Finally, I introduce the idea of employing a diverse perspective on time ('temporalities') to connect the afore-mentioned issues in a practically usable way.

2.1 Sketching the research landscape: Sustainability, transformations and metal use

My approach towards tackling the overall objective of identifying vital features of strategies that can contribute to the transformation towards (more) sustainable metal use is informed by conceptualizations of and existing approaches towards understanding sustainability, transformation processes and patterns of metal production and use, which I will sketch out in the following.

2.1.1 The research lens: Sustainability

"Sustainability has become a guiding concept in science and practice" (Luederitz et al., 2016, p. 393), as indicated also by the Sustainable Development Goals (SDGs) that formulate the global political agenda until 2030 (United Nations, 2015). For the purposes of this dissertation, the concept of sustainability serves as a normative guideline for the analysis and design of interventions in metal production and use.

Sustainability concepts and definitions vary in their focus and applicability to specific contexts, which leads to a variety of often contested interpretations (Grunwald and Kopfmüller, 2006; Luederitz et al., 2016). Especially because sustainability is a normative concept, interventions that aim to increase sustainability must therefore always be guided by a clear definition to make sure that underlying values are made comprehensible for all actors involved (Bell and Morse, 2008; Miller, 2013). Existing conceptualizations are largely anthropocentric and include an either balanced consideration of environmental, social and economic aspects or one that prioritizes the ecological dimension (Fischer et al., 2007). The differentiation of weak and strong sustainability, for example, gears to the possibility of replacing natural with human-made capital (Grunwald and Kopfmüller, 2006; Neumayer, 2013; Sachverständigenrat für Umweltfragen, 2012). But especially for resources that are non-renewable (in human time scales) such as metals, following strong sustainability would mean to not use the resources at all, if it is impossible to keep them within the material cycle. Not using metals, however, is not an option in light of their indispensability for the transformation towards sustainability (Held and Reller, 2016). A necessity to make use of metals results in the necessity to come up with 'a good way of doing it', which calls for appropriate rules for their sustainable use that are currently not in place.

Sustainability concerning metal production and use must thus follow other principles. The World Commission on Environment and Development (1987) ('Brundtland') stated that "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs." (WCED World Commission on Environment and Development, 1987, p. 41), emphasizing (i) the aspect of inter- and intra-generational equity and (ii) the consideration of limitations in the carrying capacity of the planet. Similarly, Moran and Kunz (2014, p.20) suggest to differentiate the aspects of *Sustainable Development* ("How value is distributed and shared") and *Operating sustainably* ("How activities are undertaken") in assessing the sustainability in minerals and energy supply and demand. Following the considerations of Figge et al. (2014) on assessing the sustainability of resource use, and incorporating the equity perspective of the Brundtland definition above, resource use should thus – among other – (i) create some kind of benefit to present and future generations that is (ii) equitably distributed among both present and future generations, and (iii) aim to minimize the burden associated with resource production and use now and in the future.

Sustainability science deals with sustainability problems such as those associated with (unsustainable) metal production and use, which are "often characterized by complexity, high and often irreducible uncertainty and contested values" (Miller et al., 2014, p. 240; Grunwald, 2010). It is an emerging research field that is increasingly shifting focus from understanding complex and interconnected human-environment systems (Kates, 2001; Scholz, 2011) to also include 'the commitment to moving (…) knowledge into action' (Kates, 2011, p. 19450) and actively contributing to sustainability transitions through solution strategies supported by evidence

(Miller, 2013; Wiek and Lang, 2016). This increasing solution-orientation of sustainability research calls for (i) an increased consideration of values, (ii) actively working with desirable future states, (iii) developing transition pathways, and (iv) inter- and transdisciplinary research designs that facilitate mutual learning (Miller et al., 2014).

From the perspective of sustainability, research on interventions towards sustainability in metal production and use must consider present and future aspects of well-being and equity within the limits of the planet's carrying capacity, and provide actionable knowledge to facilitate this transition process (Clark et al., 2016; Lang et al., 2012; Luederitz et al., 2017; Sarewitz et al., 2012). Three interdependent types of knowledge that transdisciplinary research relates to can also serve as guidance for the purposes of this dissertation (ProClim, 1997, Hirsch-Hadorn et al. (2008). Correspondingly, interventions in metal production and use should be informed by all three knowledge forms:

- a thorough system understanding of the complex interlinkages of current patterns of metal production and use along the whole life cycle and across the various levels and scales involved *(system knowledge)*,
- a clear idea of where to go *(target knowledge)*, and
- a comprehensive and actionable understanding of change processes and the potential contribution of interventions as concrete options to facilitate the desired change process, including an idea of how to prioritize actions based on the desired target *(transformation knowledge)*

2.1.2 The research perspective: Transformation

Resource production and use is strongly connected to the "Great Transformation" (WBGU, 2011) towards sustainability: Not only can changes in the socio-metabolic regime (Haberl et al., 2011) help to differentiate and characterize large societal transformation processes of the past. Even more importantly, many of the (technological) innovation processes we consider as relevant and inherent to the process of sustainable development are highly dependent on the availability of certain raw materials (Behrens et al., 2007; Giurco et al., 2014; Graedel and Erdmann, 2012; Held and Reller, 2016). This is especially relevant for metals, which are needed in, among many others, modern communication, mobility and energy technologies (e.g. neodymium in permanent magnets for wind turbines, indium in thin-film photovoltaics) (Angerer, 2010;

Held and Reller, 2016; Stamp et al., 2014). This also links the energy transition closely to another vital change process: a material transition ('Stoffwende') (Held and Reller, 2016; Schindler, 2016).

Interestingly, while the threat of supply risks for some metals has triggered research and governance activities towards understanding and dealing with their potential criticality (Graedel et al., 2015; Hagelüken and Meskers, 2010; Wäger and Lang, 2010), the material basis for large-scale societal transformation processes - including the energy transition - is only insufficiently considered to date (Held and Reller, 2016).

There exists, however, a large body of literature that is targeting an increased understanding of processes of fundamental change. Two - increasingly interconnected - research streams can be identified: transition research (Grin et al., 2010; Loorbach, 2007; Rotmans and Loorbach, 2010) that embarks from innovations in socio-technical systems, and transformation research (Folke et al., 2010; Olsson et al., 2004; Walker et al., 2004) that focuses on social-ecological systems. Both consider processes of intended change that takes place or is triggered on different levels, but generally follows three major phases (preparing change, the actual intervention and a stabilization of the new system state) (Moore et al., 2014), conceptualized as an s-shaped curve in the case of transitions (Geels et al., 2016).

In this context, Feola (2015) shows that scholars largely agree on defining a transformation as "a major, fundamental change, as opposed to minor, marginal, or incremental change" (Feola, 2015, p. 377) and that there is further need to comprehensively understand transformation processes. He also indicates, however, that disagreements remain regarding the consideration of transformations as the result of societal collapse or as a desirable feature of resilient systems. The research on transformation processes can be differentiated according to their purpose as being descriptive or prescriptive, i.e. attaching a certain value to the intended outcome of the change process (Feola, 2015; Loorbach, 2010; O'Brien, 2012).

Interventions can target change at different points of a system that determine how powerful the intervention is. For that purpose, Meadows (1999) differentiates and ranks twelve leverage points from shallow to deep that can potentially enable fundamental shifts. Shallow leverage points *(parameters and feedbacks)* are comparatively easy to install, but may have limited effect in achieving the desired transformation. Deep leverage points *(design and intent)* are considerably harder to implement, but may lead to large-scale and profound transformation (Abson et al., 2017; Luederitz et al., 2016; Meadows, 1999).

For the purposes of this dissertation, I will refer to both transformations and transitions as processes towards intended fundamental change, referring to *transformation* according to WBGU (2011) and to *transition* when relating to the energy transition and to transition strategies (Kay et al. 2012), unless otherwise stated.

2.1.3 The research context: Metal production and use

Over the past centuries, and as a result of an increased understanding of the functions of single elements, the total amounts, but also the variety of metals used in appliances has continuously increased, leading humanity into an "all metals age" that makes use of major parts of the periodic table (Held et al., 2018; Zepf et al., 2014).

Metal production and use and transformation processes towards sustainability are interlinked in two ways: (i) As indicated above (chapter 2.1.2), metal availability is a major contributor or even pre-requisite for the (societal) change process towards sustainability. (ii) At the same time, current patterns of metal production and use are major drivers of unsustainability or source of environmental and social threats. Intervening in the system of metal production and use with the aim to move existing patterns towards fostering sustainability therefore demands a strong systemic approach that considers both sides. Such an approach must (i) include an unraveling of the highly intertwined structures of technological, economic, and political processes, and (ii) consider that adverse effects associated with metal use occur on various spatial and temporal scales, as well as in a variety of industrial sectors and societal branches and along the whole life cycle. The multi-faceted processes and adverse effects associated with metal production and use are characteristic for sustainability problems (Kates and Parris, 2003; von Wehrden et al., 2017) and ask for comparably multi-faceted solutions (compare e.g. Achzet et al., 2010; Ali et al., 2017; Alley et al., 2008; Reller et al., 2013). These solutions must incorporate many of the above-mentioned aspects such as inter- and intragenerational equity and a fair distribution of the profits and burdens associated with metal production and use.

In the course of the past decade, metals have increasingly come to the attention of researchers and policy-makers alike. This is mainly owed to the fact that an increasing demand led to concerns over their sufficient availability, especially for some metals that have consequently been called critical or strategic (Angerer, 2010; Erdmann and Graedel, 2011; Zepf et al., 2014). While decreasing ore grades pose technological challenges for the development of mining processes that are still economically viable (Mudd, 2007; Norgate and Rankin, 2002; Northey et al., 2014; Prior et al., 2013), the potential criticality of raw materials goes beyond geological scarcity (Skinner, 1979). In that sense, the terms 'scarce metals' and 'rare earth elements' can be misleading as most metals are not geologically scarce. Many, however, are mined as a by-product of other metals and exist in smaller concentrations than e.g. gold or copper, making their extraction, concentration and purification more intricate (Kümmerer, 2016). The concept of criticality also considers (geo-) political, environmental, technological and economic factors (Achzet and Helbig, 2013; Kümmerer, 2016; Wäger et al., 2012) and differentiates supply risks, the vulnerability of the supply chain to those risks and, in some cases, the environmental impact of their supply (Dewulf et al., 2016; Graedel et al., 2015).

Approaches to tackle the challenges associated with metal production and use and work towards increased sustainability can be subsumed under the terms 'resource governance' and 'sustainable resource management'. Existing approaches include the conceptualization of overarching international governance schemes (Ali et al., 2017; Bleischwitz and Bringezu, 2008; Henckens et al., 2019) as well as smaller-scale mechanisms targeting single aspects of the resource life cycle including resource rent taxes, responsible sourcing, sustainable supply chain management and environmental standards for mining (Beske and Seuring, 2014; ICMM, 2006; MMSD Project, 2002; Prior et al., 2012). Strategies targeting sustainability along the metal life cycle can incorporate a large variety of intervention options that either focus on a specific phase of the life cycle or aim to improve their interlinked consideration including, among other, certification and labelling, standard-setting, and stockpiling (Achzet et al., 2010; Wäger et al., 2012). Exner et al. (2016) name the following main building blocks of a comprehensive resource policy: (i) supply security through primary production, (ii) technological innovation in mining, (iii) improving resource efficiency, (iv) increasing the share of recycling, and (v) material substitution. They add strategies as a sixth component, but one that intervenes in the system at a different level and can include measures to support the above-mentioned aspects.

Which interventions are appropriate or most promising depends on the specific context, must be considered in the broader context of the value chain and should be guided by the idea of using instead of consuming metals (Held and Reller, 2016). One of the most pressing challenges here is dissipation, i.e. the permanent loss of a material along the whole life cycle through their fine distribution in the technosphere or the environment (Kümmerer, 2016). Dissipation has recently increased as a result of efficiency improvements, which has led to the increasing use of a large variety of materials with very small concentrations (e.g. in smartphones) that often cannot be recovered or recycled, or not in an economically viable manner (Achzet et al., 2010). This is posing another challenge to the future availability of these materials and poses yet unforeseeable risks to the environment with regards to their potential bioactivity and toxicity (Achzet et al., 2010; Kümmerer, 2016).

2.2 Opening the research arena: Strategic approaches towards change

In this dissertation, I specifically focus on strategies as a means to intervene in systems.

The idea of developing a strategy to direct future actions originated in military contexts (Mintzberg, 1987). Later, their main area of application was in economic and entrepreneurial environments (Kaplan and David, 2008; Mintzberg, 1987) and in the sense of political strategy making (Raschke and Tils, 2013). Strategic action is defined in differentiation from tactical, operational, and sometimes also reflexive issues and tasks as being occupied with rather long-term overarching goal-setting and discussion (Loorbach, 2010; Mintzberg, 1987). Kornberger and Clegg (2011) emphasize that strategies in political processes must be understood and analyzed differently than according to the "to the neat logic of more traditional economic strategy research" (p. 137) as an active process and tool to guide processes in practice.

Strategies may be explicit or implicit, i.e. may or may not be explicitly spelled out. (In this dissertation, I focus on those that are spelled out.) They are, however, always the result of a cognitive process with a specific intention (success) they work to achieve, and pursue aims that are socially, temporally and factually extensive (Raschke and Tils, 2013).

Especially because of their diverse areas of application, there is no blueprint for strategy design, but several features repeatedly appear in the literature on management strategies as well as in intervention research and organizational change management, integrated planning and transition governance (Wiek and Kay, 2012).

(i) The process of strategy making (formulation and implementation)

In the context of decision-making, the process itself of outlining a strategy can serve a variety of purposes. For management strategies, Hart (1992) differentiates five modes of strategy making depending on the interacting roles of managers and other organizational members, their degree of involvement and the relation of rationality and visionary elements.

Probst and Wiedemann (2013) emphasize the relevance of setting up an appropriate team that formulates the strategy. The formulation process should involve all relevant stakeholders (or organizational units in the case of corporate strategies) and make sure that inhibiting factors as well as actors or actor groups are considered and team members contribute the relevant expertise as well as the necessary creativity to the process. This supports strategies that build up on the strengths of the system, but pay attention to potential weaknesses.

Regarding the implementation of the formulated strategy, Lüderitz et al. (2017) hint at the significance of the chosen process for the outcome of transition experiments through, among other, a sound methodology and a reflexive approach that enables learning throughout the experimentation phase. Loorbach (2010) introduces a transition management cycle with four not necessarily sequential components as a tool to facilitate continuous improvement, including problem structuring and visioning, developing transition paths, implementation and monitoring. In doing so, the approach links descriptive and prescriptive features of transition processes that can inform strategy making towards intended change (Feola, 2015; Loorbach, 2010).

(ii) Key elements and inputs of a strategy

Strategies should include a defined objective, a description of the initial situation from where the strategic activities embark *(the strategy environment)*, and a description of the suggested actions, which is often informed or framed by a more general understanding of the mechanisms that are meant to lead to success.

Especially in economic contexts, strategies frequently differentiate vision (as the over-arching goal) and mission (as a general understanding of how change might happen). Objectives must be manageable or usable in practice and should not be trivial (Raschke and Tils, 2013). Mission is similar to what is described as theory of change in other contexts (Kay et al., 2014; Vogel, 2012) and to what Raschke and Tils (2013) describe as the possible course for actions, including the required resources and potential pathways to success. Strategic actions should build up on and complement each other as a sequence of actions, with every item clearly referring to the strategic goal itself (Kay et al., 2014; Probst and Wiedemann, 2013; Raschke and Tils, 2013).

For the context of global transition scenarios, Raskin et al. (2002) define the major inputs for strategy making by asking the following three questions that are corresponding with the key elements described above: (i) Where are we, and where are we headed? (initial situation or current state), (ii) Where do we want to go? (defined objective or target state) and (iii) How do we get there? (suggested actions and theory of change).

2.3 Introducing a connecting element: the role of temporalities

As the consideration of present and future needs (WCED World Commission on Environment and Development, 1987) indicates, “sustainable development is an inherently temporal concept” (Held, 2001, p. 351). Bossel (1999) hints at two aspects of the temporal dimension of sustainability in particular:

1. The perception of long-term changes and future threats: Some of the problems arising from unsustainability will only pose (existential) threats to society in the (distant) future, and their pace and scale might make it difficult to perceive and establish cause-and-effect relationships, delaying necessary interventions in the system (Bossel, 1999; Held and Kümmerer, 2004; Kümmerer, 1996; Pahl et al., 2014). For the case of metal production and use, many issues from their future availability to technological innovation concerning their recyclability or substitutability and to potentially harmful impacts of dissipated materials are highly afflicted with uncertainty. This pronounces the significance of precautionary approaches and adaptive structures to incorporate risks and uncertainty in our actions (Gibson, 2006; Sellke and Renn, 2010; von Schomberg, 2006).

2. The dynamics of change towards sustainability: “Sustainability is a dynamic concept (...) and a sustainable society must allow and sustain such change” (Bossel, 1999, p. 4). Interventions towards sustainability must embrace the fact that systems are constantly changing. Natural systems in particular are characterized by temporal flexibility, which contributes to their resilience (Held and Kümmerer, 2004; Kümmerer et al., 2010). However, current approaches towards understanding and governing metal production and use, often disregard this fact. Supply and demand projections

based on static calculations such as the reserves-to-production-ratio not only disregard the relevance of metal concentration (Held and Reller, 2016; Kümmerer, 2016), but are one example for a non-dynamic and non-adaptive consideration of the resource market in general.

While research largely acknowledges spatial and temporal scales as relevant system components (compare e.g. Schwanen and Kwan, 2012), considerations of 'time' in this regard are often limited to a linear understanding in the sense of 'clock time' (Crang, 2012; Walter, 2008). Time ecology introduces a more diverse understanding of time in the sense of temporalities and emphasizes the qualitative component of time in the sense of 'making good use of time' and the right time for action ('kairos') (Adam et al., 1997; Held, 2001; Kümmerer, 1996; Kümmerer et al., 2010).

Incorporating considerations of temporal diversity in interventions in metal production and use can inform the guiding principles we apply for such interventions with regards to, among other things, aligning or balancing interventions with the natural capacity to react to disturbances (Held, 2001; Held and Kümmerer, 2004). In doing so, time ecology responds to the need of understanding systems as constantly changing and of incorporating uncertainty, perception lags and delays in the process of designing appropriate interventions (Bossel, 1999).

In the research on (governing) transformation processes, temporalities are still insufficiently addressed. In this context, Patterson et al. (2017) particularly refer to various ways in which studies "conceptualise trajectories of change over time" (Patterson et al., 2017, p. 9), and emphasize the need for capacity-building concerning long-term thinking and reflexivity in the governance of transformation processes.

A diverse understanding of the temporal dimension of change processes, which the concept of time ecology offers, could support this kind of capacity building. For the purposes of this dissertation, I am therefore employing the principles of temporal diversity to explore the connections between transformation processes, the concept of sustainability and metal production and use, and what this perspective implies for designing appropriate interventions.

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3

RESEARCH DESIGN

3 Research Design

3.1 Research Gap

As I have shown in chapter 2, a variety of challenges are opposing sustainable metal production and use as well as its effective contribution to sustainable development. A fundamental change is needed in metal production and use that can be framed as part of a material transition and which forms a vital building block within the Great Transformation. In its complexity and magnitude, this material transition is comparable to - and highly interlinked with - other change processes such as the energy transition. However, the material basis for these transformation processes is still largely underrepresented in both transformation research and policy-making, as reflected in the WBGU report on the Great Transformation (Held and Reller, 2016; WBGU, 2011).

GAP 1: It remains unclear, how we can transfer current understandings and framings of transformation processes in both research and practice to the specific case of achieving the necessary fundamental changes of the material transition, specifically for the case of metals.

Strategies as one possible means of intervention appear promising as a tool (i) to bridge the different spatial and temporal scales, (ii) to deal with risks and uncertainty in highly interwoven systems, and (iii) to guide the necessary fundamental change in this dynamic field with multiple actors involved whose idea of a desired target state may vary.

GAP 2: There is a lack of research that comprehensively covers and assesses existing approaches in a way that would provide practically applicable knowledge for future strategy making.

Considering the diverse temporalities of systems could help to draw more explicit connections between transformation, sustainability and metal production and use. It could support making sense of the heterogeneity in approaches, involved sectors, scales and organizational levels to (i) manage this complexity, (ii) achieve sustainability, and (iii) embrace change as an inherent system characteristic.

GAP 3: We have not yet sufficiently understood how these rather theoretical considerations can be applied to concrete cases of intervening in complex systems such as metal production and use.

In consideration of these research gaps and as stated in the introduction, I will therefore focus in this dissertation on the following question:

What are design features of strategies that contribute to achieving the transformation towards more sustainable metal production and use, and how could a better understanding of temporalities improve strategy design?

3.2 Overall design and overview of research articles

In this dissertation, the following four research articles contribute to the research objective of identifying design features for strategies to contribute to more sustainable metal production and use along their whole life cycle:

P1 **Putting sustainable chemistry and resource use into context: The role of temporal diversity**
Annika Weiser, Daniel J. Lang, Klaus Kümmerer
Published in: Sustainable Chemistry and Pharmacy 5 (2017) 105 - 114

P2 **Acknowledging temporal diversity in sustainability transformations at the nexus of interconnected systems**
Annika Weiser, Lotte M. Lutz, Daniel J. Lang, Klaus Kümmerer
Published in: Journal of Cleaner Production 162 (2017) 273 - 285

P3 **Understanding the modes of use and availability of critical metals – An expert-based scenario analysis for the case of indium**
Annika Weiser, Daniel J. Lang, Thomas Schomerus, Anna Stamp
Published in: Journal of Cleaner Production 94 (2015) 376 – 393

P4 **Towards a more sustainable metal use – Lessons learned from national strategy documents**
Annika Weiser, Manuel W. Bickel, Klaus Kümmerer, Daniel J. Lang
Submitted to: Resources Policy (December 2019)

The approaches and focal points of the individual articles complement each other and each respond to one or several of the research gaps. A conceptual part (papers P1 and P2) explores the role of temporalities for interventions in complex and interlinked systems, which adds to the conceptual basis, on which the empirical part (papers P3 and P4) builds up to explore present and future interventions in metal production and use.

The conceptual work is driven by the question, how we can improve system understanding and intervening in complex and interlinked systems through the explicit consideration of temporalities and the appliance of the principles of temporal diversities. P1 focuses on the relation of temporalities to space, knowledge and action under uncertainty through the analysis of aspects of temporal diversity in past and present cases from sustainable chemistry and metal production and use. It focuses especially on the role of precautionary and adaptive approaches. P2 explores the role of temporal diversity in guiding system understanding and interventions in interconnected systems, taking the mineral-energy nexus as an example. The results have implications for closing research GAP 3 with regards to the consideration of temporalities in system interventions. They inform the main research objective of identifying design features for strategies through the formulation of general principles (P1) and guidelines (P2) for such interventions.

The empirical work is driven by the question how existing intervention options and strategic approaches are interlinked and influencing each other, and how these activities are (jointly) contributing to the objective of more sustainable metal production and use. It consists of two parts: For P3, I conducted a formative scenario analysis that analyzed the interplay of different intervention options (technology options and governance interventions) targeting metal criticality for the case of indium and for the reference year 2030, and appraised the robustness of the scenarios against the background of four global shell scenarios. The collection and assessment of intervention options as well as the robustness appraisal were based on literature study and expert interviews. For P4, I analyzed 37 national strategy documents, which targeted either mineral resource use in more general terms or metals in particular, regarding their objectives, focus and the suggested strategic actions. I evaluated the data using MS Excel, but also applying an exploratory cluster analysis and a multiple correspondence analysis using R (R Core Team, 2018) to identify useful patterns and principles to be applied in future strategy design towards more sustainable metal production and use. The results have implications for closing GAP 2 regarding concrete recommendations for future strategies based on this comprehensive analysis. P4 also has implications for closing GAP 1 as the study applies established conceptualizations of transition processes to the analysis of existing strategy documents. They inform the main research objective of identifying design features for strategies by presenting insights on the role of single interventions in contributing to more sustainable metal production and use and by formulating recommendations for strategies in relation to both content- and process-related factors of strategy design.

Fig. 3 locates the three research gaps and illustrates how each study is embedded in the conceptual frame of this dissertation and how it contributes to the overall research objective. Table 1 gives an overview of the different perspectives and approaches of each study as well as the main results of each study and their main contribution to the main research objective of this dissertation.

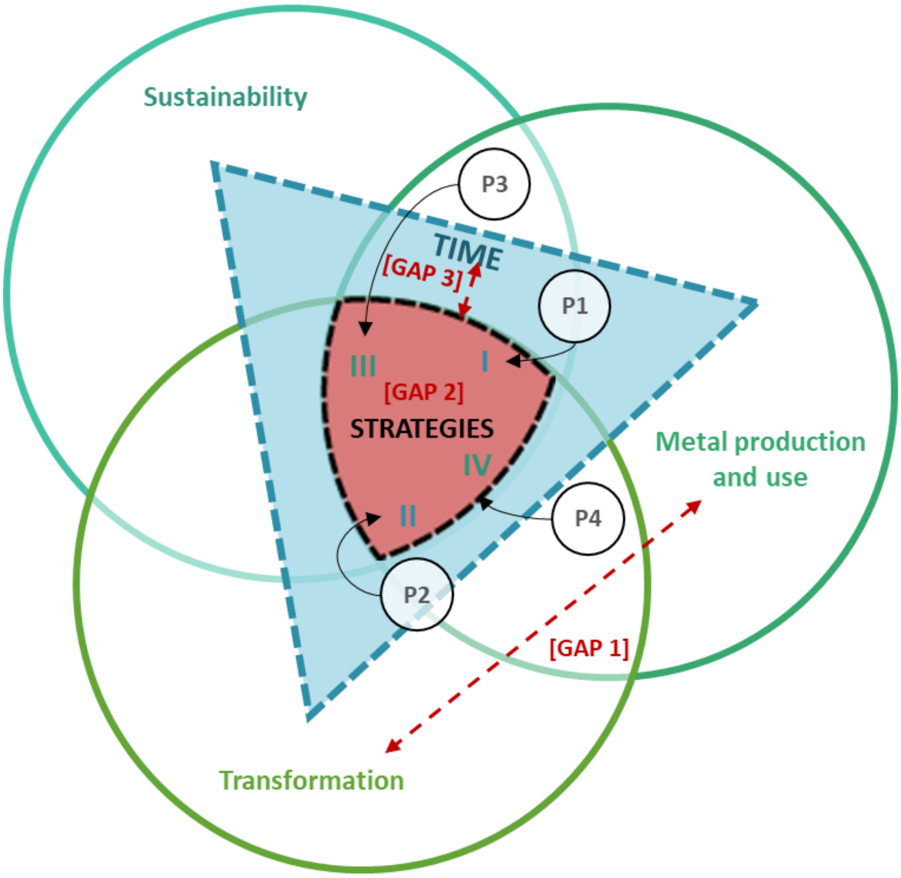

Fig. 3: Conceptual frame highlighting strategies as the main focus of research and supplemented with the location of the three research gaps (in red writing) and each of the studies (P1 to P4), their contribution to the overall research objective (numbers I to IV indicate the individual contribution to design features for strategies and are further explained in Table 1)

Table 1: Overview of the four research articles of this cumulative dissertation comparing each study's focus and scope, temporal perspective and methodical approach, and stating the main findings for the purposes of this dissertation, the research gap(s) that the study mainly addressed and the main implications for strategy design

	P1	P2	P3	P4
TITLE	**Putting sustainable chemistry and resource use into context: The role of temporal diversity**	**Acknowledging temporal diversity in sustainability transformations at the nexus of interconnected systems**	**Understanding the modes of use and availability of critical metals – An expert-based scenario analysis for the case of indium**	**Towards a more sustainable metal use – Lessons learned from national strategy documents**

	P1	P2	P3	P4
FOCUS + SCOPE	sustainable chemistry and resource use // world-wide examples	mineral-energy nexus // general considerations	critical metals (indium) // Germany	metals // world-wide comparison of national documents
PERSPECTIVE	past and present)	present	future: scenarios for 2030	present: status quo of existing strategies
APPROACH	<u>conceptual study</u> - literature-based study - illustration with selection of practical examples	<u>conceptual study</u> - literature-based study - application to mineral-energy nexus	<u>empirical study</u> - expert interviews - formative scenario analysis - robustness appraisal	<u>empirical study</u> - criteria-driven analysis of policy documents - exploratory cluster analysis and multiple correspondence analysis
MAIN FINDINGS OF THE STUDY	- insights on the interconnections of temporal diversity and space, knowledge and action under uncertainty can enhance precautionary approaches and support adaptive governance concerning - (i) what determines the consequences of an event, - (ii) the source of a disturbance that might be outside the considered scope of action and observance, and - (iii) the improved understanding of the rhythmic nature of natural systems that increases their resilience	- temporalities unfold particular relevance for interventions in interconnected systems (such as the mineral-energy nexus) that cross various scales, fields of action or regulative levels - presenting a three-step time-in-transformations-approach that links principles of time ecology with conceptualizations of transformation processes - enables better (temporal) system understanding and informs interventions considering a system's inherent time scales and other temporalities and placing an intervention according to the desired effect	- identification and analysis of the systemic and perceived future relevance of intervention options (technology and governance) - four scenarios exploring the interplay of the interventions and their potential contribution to dealing with indium criticality - business as usual is not an option (trend exploration), neither is a focus on one life cycle phase (recycling society) or regulative level (stringent regulation); instead, a comprehensive approach that involves the private industry is needed (world of cooperation) - a balanced approach also increase robustness in changing environments	- identification of four clusters of strategy documents that share certain (geographic or economic) context conditions and similarities in their approaches - clusters differ in their objectives, focus on different life cycle phases and relate differently to sustainability: (i) upscaling exploration, (ii) mining for development, (iii) our resources for our industry, and (iv) closing cycles, securing supply - strategies need a clear structure and target
MAINLY ADDRESSES	**GAP 3**: minimizing risks, acting under uncertainty	**GAP 3**: sustaining and strengthening resilience	**GAP 2**: understanding the interplay of interventions; aiming for robustness and a balanced approach	**GAP 2**: making sense of the existing heterogeneity of approaches // **GAP 1**: establishing strategies for intended change
IMPLICATIONS FOR STRATEGY DESIGN	**I.** three basic principles for integrating temporal diversity: (i) use time as an integrative factor; (ii) find windows of opportunity; (iii) build long-term strategies with precaution	**II.** insights for a more precise system understanding; guidelines to inform intervention design: (i) avoid temporal misfits; (ii) minimize negative impacts, (iii) acknowledge or reduce delays	**III**. insights on interventions' role and interplay in developing pathways towards sustainable metal use	**IV**. recommendations for strategy design (process and content) including the description of the current and target state as well as concrete transition actions for each group

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4 RESULTS

4 Results

4.1 Putting sustainable chemistry and resource use into context: The role of temporal diversity

Annika Weiser, Daniel J. Lang, Klaus Kümmerer

Abstract

Fostering sustainability implies the use of better technologies, chemicals, materials, and industrial processes. This makes chemicals and resources such as metals inevitable components of and contributors to the envisioned societal sustainability transformation. At the same time, they are the source of various adverse effects that ought to be addressed and minimized, including waste and environmental pollution. Often, negative impacts are highly interconnected or only become visible after considerable time, which makes it difficult to identify cause- and-effect relations. We postulate that we must find ways to comprehensively incorporate the spatial and temporal scope of our actions, their (unintended) effects, and the opportunities that they offer for decision-making processes. The latter should be based on a clear understanding of the underlying knowledge, uncertainties, and the related times. In this article, we specifically discuss the role of time and temporal diversity at the interface of space, time, knowledge, and action. We show potential consequences that arise from considering the temporal dimension with regards to the precautionary principle. Based on major findings from time ecology, we suggest guidelines to acknowledge temporal diversity that could contribute to developing solutions with a long-term contribution to sustainability. The guidelines put special emphasis on a more profound understanding of a system's delays, the definition of windows of opportunity, and on designing interventions in accordance with a system's interconnected times.

1 Introduction

Fostering sustainable development implies and is inextricably linked to the use of suitable and improved technologies, chemicals, materials, and industrial processes. It affects fields of action as diverse as environmentally-friendly clothes-dyeing, modern communication, and low-carbon energy production. This makes chemicals and raw materials such as metals inevitable components of this fundamental change (Exner et al., 2016; Kümmerer and Clark, 2016; Moss et al., 2011). Many of the United Nations (UN) Sustainable Development Goals (SDG) signed in 2015 have some link to chemistry, and are calling for a prudent use of material resources, chemicals, materials, and products (United Nations, 2015). This, too, underlines chemistry as an integral part of a sustainable future (Kümmerer and Clark, 2016). But while the positive implications and the contribution of chemistry to our well-being, health, and standard of living cannot be dismissed, the risks and adverse effects associated with chemical use are just as evident.

Humans have visibly shaped the face of the planet over time. At an early stage, sedentism characterized the agrarian society. Impacts have increased strongly ever since the start of the industrialization (Haberl et al., 2011). Since the 1950s, various aspects – from population growth to energy and fertilizer use to ocean acidification – show similar patterns of sharp increase. This has become known as the Great Acceleration (Rockström et al., 2009; Steffen et al., 2015). Today, our impact on the functioning mechanisms of the planet, including its energy balance, its biological basis and the system of stocks and flows, cannot be ignored. This has led us into the age of humans, or Anthropocene (Biermann et al., 2015; Crutzen, 2002; Steffen et al., 2007). It has close links to the concept of planetary boundaries, which is also very relevant to chemistry: Keeping chemical pollution within the safe operating space bears significant challenges due to the large amount of different chemicals in use on a world-wide scale (Diamond et al., 2015).

Chemical use has caused many environmental burdens as well as health issues in the past. Prominent examples include male infertility of workers in production plants and plantations following the production and use of the pesticide Dibromochloropropane (DBCP), and the harming effects of tributylin (TBT) and its follow-up booster biocide antifoulants on marine habitats (European Environment Agency, 2013). Continuous threats do not only arise from ongoing emissions of untreated waste, waste water and exhausts. They also come from past catastrophic events and accidents such as the Bhopal gas tragedy of 1984 or the Sandoz chemical spill in Schweizerhalle in 1986. Nowadays, broad-scale regulations, mechanisms, and technologies are installed for treatment and prevention of emissions at least in most developed countries. At first sight, many of these challenges seem to have been generally overcome. However, it must be kept in mind that a lot of the manufacturing and synthesizing processes have been moved to facilities in developing countries, where regulation is less strict or less strictly enforced (Kümmerer and Clark, 2016). And also in industrialized countries legacy issues remain largely unsolved: Persistent substances such as POPs (persistent organic pollutants) have accumulated in animals and humans, and have contaminated the environment over a period of many decades. They continuously leach into and volatilize in the environment, as illustrated by the case of insecurely stockpiled hexachlorocyclohexane (HCH). Even advanced effluent treatment cannot prevent the emission of chemicals and pharmaceuticals into the aquatic environment (Kümmerer et al., submitted; Schwarzenbach, 2006). This shows that further action must be taken towards the identification and safeguarding of the respective contaminated sites (Vijgen et al., 2011; Weber et al., 2012).

Metals mining and use are associated with comparable problems and challenges (Held and Reller, 2016; Kümmerer, 2016; Kümmerer and Clark, 2016). Among others, environmental hazards and social problems in the course of the extraction and purification process make the need to find solutions for these challenges an urgent matter (Ayres, 1997; Bridge, 2004; Exner et al., 2016; Mudd, 2007; Nansai et al., 2015). A broad range of studies relates to the matter of future availability and possible impacts on the industry through supply bottlenecks. Studies largely focus on critical or scarce metals, especially for specific purposes such as their use in low-carbon energy production or other emerging technologies. They provide information on supply estimates and material flows or discuss potential solution strategies (Chancerel et al., 2009; Commission of the European Communities (EC), 2014; Giurco et al., 2009; Graedel et al., 2012; Jackson et al., 2014; Strothmann et al., 2013; UNEP, 2011; Wäger et al., 2012; Weiser et al., 2015).

The potentials and challenges for sustainability in chemistry in general and metal use in particular are highly connected. The flows of materials, substances, and products are increasingly interlinked in a globalized economy, and the related time scales are getting larger and more diverse (Held and Kümmerer, 2004). Our actions have an impact on increasingly larger spatial scales, which also implies a growing need to closer consider temporal scales: (i) past actions continue to have an impact in the present and in the future; (ii) just like the spatial impact, the time scales associated with our actions increase in length; (iii) with a growing global interconnection, such large-scale processes are also increasingly difficult to oversee. This makes it hard to establish (linear) cause-and-effect relations in the case of unintended effects, and demands us to take action in the light of uncertainty.

Spatial and temporal scales are highly interwoven (Held and Kümmerer, 2004; Kümmerer and Held, 1997a). Several studies exist that incorporate or elaborate on the role of temporal and spatial scales and their interrelations (Crang, 2012; Fresco and Kroonenberg, 1992; Held, 2001; Schwanen and Kwan, 2012). The literature on risks and impacts of our actions elaborates on the strong interrelation of knowl- edge and uncertainties, and how the latter can make decision-making a challenging task (e.g. (Renn, 2008; Sellke and Renn, 2010; Speirs et al., 2015; von Schomberg, 2006)). Little research, however, seems to exist on the interrelation of all four aspects: time and space, knowledge, and action. One factor has largely been neglected in particular: the role of time and its impact on how we interpret our actions in relation to our knowledge base and scope of action. As we have argued above, these interrelations will be increasingly important for decisions based on a long-term and global perspective in order to achieve sustainability. We claim that

- to adequately deal with risks and uncertainty, we also need to understand the connections of space, time, knowledge, and action, including the question of responsibility for our actions in relation to time, and that
- by operationalizing and integrating temporal aspects into our research and actions more explicitly and with a close relation to their spatial scope, we can increase our understanding of (complex) systems, and contribute to better decision-making that reflects a responsible management of information, knowledge, and uncertainty.

In the following, we will sketch out challenges and concepts on the path towards sustainable chemistry and resource use, focusing on approaches to deal with adverse effects in the light of uncertainty (section two). In section three, we present basic principles of the time ecology concept, which considers time and its different forms as a vital system feature, as a conceptual basis for a stronger consideration of time in decision-making and actions. Section four illustrates the potential contribution of time ecology considerations with regards to sustainability and risk management. Finally, we provide concrete guidelines for the incorporation of temporal dimensions in research and action towards sustainable chemistry and metal use (section five).

2 On the path towards sustainable chemistry and resource use: Challenges and concepts

Two complementing perspectives on moving towards sustainable chemistry and resource use are sketched out in the following: (i) making the functions and services offered directly or indirectly by chemicals, chemical products, and metals sustainable, and (ii) managing the negative impacts and challenges associated with making use of these resources (compare Wäger et al., 2012).

2.1 Introductory thoughts on sustainable chemistry and resource use

Sustainable chemistry has evolved from environment-focused approaches like the German Enquete-Kommission (committee of inquiry) on sustainable material flows in the 1990s (Enquete-Kommission, 1994), the formulation of the 12 principles of green chemistry (Anastas and Warner, 1998), and international approaches such as the UN initiative for the better management of chemicals (UNEP, 2006). Recently, sustainable chemistry has been acknowledged as a cornerstone for sustainable development by the second United Nations Environmental Assembly (UNEP, 2016). It includes economic, social, and ethical aspects as well as new business models (Kümmerer and Clark, 2016). Achieving sustainable chemistry goes beyond improvements in synthesis, compounds and products, and "include[s] the contribution of such products to sustainability itself" (Kümmerer and Clark, 2016). New business models like chemical leasing are meant to create win-win-situations between the customer and provider of, e.g., solvents or disinfectants, by offering a service or functionality rather than trying to sell as much of a chemical product as possible. Such business models have the potential to considerably reduce or avoid resource and energy consumption, and chemical-related environmental burdens (Kümmerer and Clark, 2016; UNIDO, 2016). Nevertheless, the use of chemicals remains largely unsustainable, and new models can only be understood as the beginning of a broader transformation process.

Also for the case of mining, attention has broadened over time; from purely environmental aspects to a more inclusive scope incorporating aspects such as indigenous rights (Bridge, 2004). Today, several mainly international frameworks and initiatives aim to provide guidance for policy and industry towards achieving sustainability in the mining sector, such as the Global Reporting Initiative (GRI), the Extractive Industries Transparency Initiative (EITI) or the Natural

Resource Charter (Buxton, 2012). Efforts on the mine site itself have evolved from single initiatives to more established concepts for sustainable mining (Barume et al., 2016; Corder et al., 2010; Fitzpatrick et al., 2011).

Discussions on sustainability and metals have mostly evolved around two core statements: On the one hand, metals are considered to be non-renewable; on the other hand, they can be recycled to a certain extent and thus be kept within the economic cycles (Held and Reller, 2016; Reck and Graedel, 2012; Speirs et al., 2015; UNEP, 2013a). However, thermodynamics tells us that such an infinite use is not possible in the long run. For technical, energetic, entropic or economic reasons, metals might not be usable or accessible any more at some stage (Kümmerer, 2016). Dissipation is unavoidable; we can only aim to reduce its degree. This makes dissipation one of the major challenges opposing sustainable metal use: the increasing mixture of materials in appliances and devices does not only make recycling more and more difficult, but fine particles distributed (dissipated) in the environment might also accumulate and become toxic (Held and Reller, 2016). Other sustainability challenges related to metal use include the amount of energy needed for grinding ores and recycling, or the health hazards for workers in electronic waste recycling in countries of the Global South. To address these challenges, we need to increase our knowledge on substance flows, fate and behavior.

2.2 Managing risks and dealing with uncertainty

While existing approaches indicate that we do have a more or less concrete idea of how sustainability in chemistry and metal use could and should look like, questions remain on how to get there, and how to solve the remaining challenges. One major, very practical question is how to minimize adverse effects of metals and chemicals use and to achieve an actual contribution to sustainability.

In contrast to hazards, which "describe the potential (...) to cause harm to what people value", a risk evolves as soon as "there is a likelihood that this potential is released in a way that it produces harm" (Renn, 2008). Both hazards and risks are afflicted with uncertainty regarding the impact of our actions on various spatial and temporal scales, thus connecting the four aspects of knowledge, action, time, and space. Renn et al. (2011) introduced systemic risks as a new type of risk that is characterized by "complexity, uncertainty, and ambiguity" and also impacts other sectors and risks outside the observed system. Using the case of active pharmaceutical ingredients (APIs) in drinking water, Keil et al. (2008) emphasize that this also demands an appropriate risk governance approach for highly interwoven, complex systems. Systemic risk governance builds upon the original idea of risk governance that incorporates risk assessment, management and communication (Renn et al., 2011; Sellke and Renn, 2010). Additionally, it aims to consider interdependencies and impacts between risks that may seem unrelated at first (Renn et al., 2011). Adverse effects increasingly unfold in the long-term and on a global scale (Renn et al., 2007). Scientific and socio-political approaches, however, remain rather short- term (Kümmerer, 1996). Systemic risks can, in that context, be described as delimited (entgrenzt) in terms of place and time, but also regarding the categorization of the caused harm (Renn et al., 2007). An increasing speed of change and globalized expansion of harmful effects may then result in a "trans-boundary impact" of risks (Sellke and Renn, 2010).

Examples for risk in relation to chemistry or metal use include (i) adverse effects from toxic (heavy) metals in the environment, which also applies to the use of rare earth elements, and (ii) supply bottle- necks, since resource availability estimates are often contested and uncertain. Confusion and uncertainty even increase when estimates fail to capture socio-political and sustainability factors (Speirs et al., 2015). Many studies, therefore, emphasize the need to differentiate reserves, reserve base and resource (Gordon et al., 2007; USGS, 2016; Wäger and Lang, 2010), and to critically reflect upon the reliability of estimates in relation to time (Kümmerer, 2016).

It remains open, how exactly we should be incorporating both spatial and temporal scales and other temporalities into our processes of decision-making and assigning responsibilities. The precautionary principle is a prominent instrument that is used to legitimize actions despite suspected risks and initial uncertainty (Keil et al., 2008). As a general principle, the burden of proof is put on those that would expose the public to a potential risk. They must provide sufficient evidence that a planned action is not harmful despite initial "reasonable grounds for concern" from the scientific community (von Schomberg, 2006). The principle has found its way into some areas of European Union legislation as well as into international agreements (e.g. in the 1992 Rio Declaration) (Commission of the European Communities (EC), 2000).

3 A more diverse perspective on time: time ecology principles

Time ecology elaborates on the relevance of time for environmental issues in policy and practice. Research focuses, but is not limited to, resource depletion, pollution, and the unsustainable use of non-renew- able resources. All of these topics are associated at their core with human actions and speed of change at "rates incompatible" with natural systems (Adam et al., 1997). Analogous to landscape, the concept of timescapes incorporates several basic elements of time ecology and strongly emphasizes the role of spatial as well as temporal context to find and evaluate sustainable pathways (Adam, 1998; Hofmeister and Kümmerer, 2009).

Two sets of ideas are of particular relevance for the work at hand:

(i) *Temporal diversity + polyrhythmicity:*

Through combining specific temporal elements (point of time, time line or period) and temporal relations (before, simultaneous, after), we can gain a deeper understanding of the diversity of possible time forms such as its direction and extension, the duration of an event and occurring change, and the forming of the unique times of past, present and future (Kümmerer et al., 2010). It is important to note in this context that there is usually more than one time that needs to be included into our considera- tions. Time is usually regarded as one-dimensionally, and per- ceived as measurable clock time or calendar time (Held, 2001). Each system (e.g. organism or ecosystem), however, has its own inherent time scales (Eigenzeiten (Kümmerer, 1996)) and slightly varying rhythms. Natural systems owe a certain resilience to this kind of temporal flexibility (Kümmerer et al., 2010), but cause and effect can be difficult to distinguish (Kümmerer, 1997).

(ii) *Perception of time, time lags and delays:*

Besides measurable Newtonian time (Held, 2001; Kümmerer et al., 2010), which gives time a rather descriptive notion, it also has a strong qualitative component. This means that there is a right time for action ("kairos") and that time can be perceived quite differently depending on the context of the concerned person as well as the spatial scale of a system (Kümmerer, 1996). On-going changes and their effects might only become visible after a long period of time and might even then not be observed immediately. Even more time will pass until people react and until the effects of this reaction in turn are noticeable, as observed in the 1980s for chlorofluorocarbons (CFCs) and the ozone layer (Held and Kümmerer, 2004; Kümmerer, 1996; Molina and Rowland, 1974).

4 Temporal diversity in sustainable chemistry and resource use

4.1 The role of time in sustainable chemistry in general and in metal use

Sustainable chemistry is by its very nature not a new, well-defined (sub-) discipline, but a dynamically changing and cross-disciplinary approach within and beyond chemistry, which in turn is related to a wealth of times. Behind the scene, many additional temporalities such as *Eigenzeiten*, rhythms, beats, windows of opportunities, delays, starting points etc. are involved: Dissipation can be considered a lingering process; product life times or mine production rates might be increasing or decreasing. For the case of dissipation, the time scales of loss strongly depend on the type of use and concentration in different products (Kümmerer, 2016). The differentiation of renewable and non-renewable resources, including their consumption and regeneration rates, also depends on the applied time scales.

Raw materials are used because of the functionalities they offer (e.g. electrical conductivity in the case of metals), and function is closely related to a certain life time. Sustainable chemistry sets out from there: What are the functions needed for sustainable development and how can these be offered by chemical science and its products in a sustainable manner? It aims for an improvement of a material's functionality and includes non-chemical or technical issues such as child labor, an absolute reduction of resources, or rebound effects. Since sustainable chemistry is considered to be an indispensable building block for a sustainable future (UNEP, 2016), it must be based, among other things, on a better understanding of the broader context. Taking the various forms of time (temporalities, timescapes) into consideration and better understanding their significance in this context is highly relevant.

4.2 The role of time in managing adverse effects

Dealing with systemic risks is also a matter of defining and dealing with the spatial and temporal scales involved. The points in time when risks emerge or are perceived, the duration of their persistence, or the moment that action can or will be taken are often highly interwoven or inter- connected and depend on the inherent times of a system, e.g. its reaction time. Larger spatial scales are often connected to larger temporal scales. It is thus difficult to understand potential adverse effects in large systems, increasing the need for precaution. Graßl (1993) accordingly recommends to always set off at the largest possible scale and "downscale" from there. It holds true, also for the case of chemical and metal use, that past actions often define the future (Kümmerer, 1997): Brownfields, former sites of landfills and garbage dumps, are continuously releasing pollutants into the environment. Following generations are still affected by the use of Agent Orange in Vietnam. And metals that have been dissipated into the environment will not be recollected anymore, creating a lasting effect in terms of potential supply shortages. However, taking proactive action despite some uncertainty about cause and effect will always create a dilemma for decision-makers. This is called the paradox of precaution: "If a chosen measure is successful the risk at hand won't materialize; consequently it is impossible to verify with hindsight if there would not have been a less intrusive, less costly solution to cope with the anticipated risk" (Keil et al., 2008). This is similarly discussed as the Collingridge dilemma, which has been challenging the thinking behind technology assessment since the 1980s: At an early stage of implementation, the societal impact of a new technology cannot be reliably assessed. As soon as it has properly been established within the society and its impact becomes visible, however, it is often already too late and economically unviable to reroute. The challenges associated with decision-making under uncertainty or ignorance therefore strongly emphasize the role of (techno-) political processes (Böhle, 2009; Liebert and Schmidt, 2010).

4.3 Sustainable chemistry, risk, and time: Learning from practical cases

Bringing together the afore-mentioned aspects of time ecology, precaution, and systemic risk governance raises a variety of questions: Who is responsible, when the cause of an adverse effect cannot be identified, or when the cause was probably the result of a combination of several factors in different locations (or even times)? How can we define a potential danger, when effects might only manifest beyond time scales we are capable of anticipating? How to cope with changes that cannot be halted anymore by the time we observe them? To what extent are we even able to anticipate potential hazards in complex systems?

Table 1 below illustrates these challenges with (i) phenomena or mechanisms like dissipation and market dynamics, and (ii) specific examples for the cases of sustainable chemistry and metal use. For each, aspects related to temporal diversity are described and some lessons learned for decision-making and planning are indicated.

Table 1. Practical examples and lessons learned

Practical example	Aspects of temporal diversity in the connection of time, space, knowledge, and action	Lessons learned
Dissipation		
▪ Platinum and rhodium used as catalysts in converters to remove nitrous oxides from vehicle exhausts result in the dissipation of these metals along road sides (Helmers, 1997; Helmers and Kümmerer, 1999), from where they cannot be reclaimed anymore in an economically viable manner. ▪ Rare earth elements (REE) used in, e.g., batteries in hybrid or electronic cars, permanent magnets, loud speakers, wind turbines (Golev et al., 2014): often, one product contains many of these elements at the same time and at different concentration levels and compounds.	▪ Products as the main emissions and intended pollutants of the future; may also contribute to the dissipation and thereby inevitable loss of resources (De Man and Friege, 2016; Exner et al., 2016; Held and Reller, 2016; Kümmerer, 2016). ▪ Short-sighted use in the light of dissipation, supply bottlenecks and uncertainty about stocks, especially for critical metals. ▪ Recollection is i.a. bound to time scales and points in time of technology development, economics and culture.	Precaution: ▪ Use only, what can be recycled (under given restrictions of chemical properties, type of product, possibility of recollection). ▪ Collect (if possible) and stockpile, where a viable recycling technology is in sight or can be developed in the future (see Section 5.2).
Market dynamics		
▪ Companies react to potential supply bottlenecks by (re-) opening additional mining and production sites or capacities. It might take up to 10 or 15 years to bring a mine into operational stage, i.e. other solutions must be found for ad-hoc reactions. ▪ Innovation and fashion cycles may be much shorter and changes much quicker than the time that is needed for improvement, adaptation or new development of technology or recollection systems	▪ Complex dynamic resource markets call for quick reaction and adaptation to occurring changes. ▪ Need to keep some degree of (temporal) flexibility to preserve resilience.	Interconnections: ▪ Emphasizes the need to harmonize time scales and rhythms of the various systems involved (compare Section 5.1: "Fehlerfreundlichkeit").
CFCs, the ozone layer, and the Montreal Protocol (1980s)		
▪ Delay of taking action due to politics and industry asking for "more explicit proof of scientific assertions to that effect", where there would have been the need to act even before there was "incontrovertible proof of undesirable and unexpected consequences" (Kümmerer, 1996).	▪ Procedure ignored the natural time scales behind the stratospheric processes that led to ozone depletion.	Scales: ▪ The bigger the time scales of the involved systems, the less we can establish a cause-and-effect relationship and the more important it is to act according to the precautionary principle.

▪ Resulted in an on-going increase of CFCs for another 20 years even after production was stopped worldwide with the implementation of the Montreal Protocol (Kümmerer, 1997; Molina and Rowland, 1974).		
Lead production and consumption		
▪ Industrialization of lead production, refinery and consumption processes led to sharp increase of lead concentration in the environment. Lead in paint is still an issue in developing countries (SAICM, 2016). ▪ Aggravated situation in recent years especially in African countries through a lack of minimum standards for managing lead-acid car batteries. Practices result in serious health impacts for workers, but also the larger society (e.g. cross- contamination into other products like water tanks) (Manhart et al., 2016).	▪ Temporal and spatial scale of actions and their effects too big to halt the development or make effects undone (Heyworth et al., 2009; Kümmerer and Held, 1997b; Marx et al., 2016). ▪ Case of delayed perception in large-scale systems, lack of knowledge on unintended side-effects.	Delays: ▪ Inherent time scales of a system must also include the time a system needs to visibly or measurably react to and recover from any disturbances (Held and Kümmerer, 2004).
Asbestos		
▪ Warnings were formulated as early as 1898, but was only banned in the late 1990s (European Environment Agency, 2001). ▪ Asbestos has more harmful effects together "with tobacco, and some endocrine disrupting substances" (European Environment Agency, 2013). (similar: polychlorinated biphenyls and brominated flame-retardants	▪ In systems with long time scales, a clear correlation of cause end effects in a conventional scientific sense is not possible anymore: Delay of effective regulative action despite indications that asbestos might be harmful, leading to a continued number of fatalities. ▪ Use even continues, especially in developing countries, i.e. large discrepancy of knowledge and action despite long-term proof. ▪ Control measures ignored the latent period of 10–40 years and role of exposure to a mixture of stressors.	Monitoring and evidence: ▪ Need to establish institutional structures for long-term monitoring. Take into consideration short termed action and its long term effects. ▪ Having no evidence for harm does not equal having evidence for harmlessness (European Environment Agency, 2001). ▪ Need for precaution: Threat of delayed action due to interference of science and knowledge with other interests (e.g. economical ones) with shorter time scales.
Chemical toxicology & long-term accumulation		
▪ Persistence (of organic pollutants) considered in chemical assessment as key criterion in Stockholm Convention on Persistent Organic Pollutants, but might take decades to	▪ Delay of reaction and impact of action. ▪ Disconnect/ Distortion of time scales in human and natural systems, challenge for perception and reaction:	Inherent time scales: ▪ Precaution should bear in mind the associated time scales, especially when effects can already be known and weighted.

reach understanding on toxicology and put pollutants on the list (for metals also compare Minamata Convention in Mercury (UNEP, 2013b).

- Heavy metals accumulating in sediments and affecting organisms, also observed for some REE only shortly after their increased industrial processing and use.
- Co-mobilization of thorium and uranium (mining of REE or low-quality phosphate): Long period of time underground (harmless), comparatively quick extraction, followed by again a very long period of time of mobilization and persistence in the environment (due to extremely long radio-active half-life).

persistence means long time scales, even when their actual use phase was rather short.

5 An appeal for a more distinct use of time in sustainable chemistry and resource use

The implications that can be drawn from time ecology have not yet unfolded their full potential within sustainable chemistry and metal use. An enhanced awareness for the variability of possible time forms could considerably deepen our understanding of a system's dynamics and interrelations.

5.1 Connecting temporal diversity and space, knowledge, and action under uncertainty

Temporal impact assessment is a useful method that provides guidance in highly interconnected timescapes. It emphasizes the role of temporal aspects in the assessment of ecological impact and material and substance flows (Hofmeister and Kümmerer, 2009; Kümmerer and Hofmeister, 2008) and helps to unveil long-term effects by adjusting scales of change and scales of observation to each other. In doing so, it could inform strategies and planning processes in the fields of mining and technology development, or in the transition to sustainable chemistry.

Certain time scales might be too long to allow humans to determine causal connections. By demanding unambiguous proof for the cause of a certain hazard, valuable time might pass in vain and the adverse effects might even increase in these cases. The question of our ability to anticipate risks that might evolve in the far future also challenges today's established law-making procedures. As legislation aims to regulate what is already there, it contradicts the idea of taking action before adverse effects even appear. This contradiction emphasizes not only the need for anticipatory governance (Guston, 2014), but draws the attention once more to a precautionary approach that acknowledges temporal diversity. The precautionary principle can serve as guidance to meaningfully complement existing legislation, which could also be applied more broadly in the fields of chemistry and metals use. To a certain extent and under specific circumstances, it can be an appropriate instrument to operationalize the interlinkages of time, space, knowledge, and action as well as responsibility in a rather formalized way:

a. It helps to define formal procedures for dealing with uncertainty regarding the spatial and temporal extent of the impact of our actions. These procedures would have to consider that a potential hazard may have its source outside the (temporal, spatial and/ or regulatory) frame of the area of application of the precautionary principle.

b. It could complement established regulatory procedures by offering the possibility to take action even before there is full evidence for a potential hazard. It thus allows to better avert damage, instead of limiting the effects of something that has already occurred and avoiding a future re-occurrence.

It is vital to acknowledge that risks are not only created through unplanned events, but also through the very normal mode of operation (compare Keil et al., 2008). In a world of growing complexity, accepting uncertainty about causal relations as given would frame a new scientific paradigm and form an important characteristic of sustainability, for example in toxicology or risk assessment. Uncertainty, in that respect, is then "no longer an enemy [...] but a basic property of the world to understand the challenge of irreversibility" (Held, 2001). This approach is comparable to what Christine and Ernst Ulrich von Weizsäcker defined as *Fehlerfreundlichkeit* (error-friendliness). They call for a deep engagement with deviations from the expected and establish the readiness to assume risk as a precondition for action (Weizsäcker and Weizsäcker, 1984).

5.2 Basic principles of integrating temporal diversity into sustainable chemistry and resource use

With regards to the (sustainability) challenges depicted in this work, we propose the following principles for an integration of temporal diversity into sustainable chemistry and resource use.

5.2.1 Use time as an integrative factor

Chemistry and resource use should consider time – in relation to space – as one central integrative factor or common denominator that enables a comparison and possibly an assessment of the potential impact of single factors and events. As an example, metal availability issues might appear in a different light, when the various factors contributing to a metal's criticality (from geological and technological to geo-political and ecological (Wäger and Lang, 2010)) are brought together based on their inherent time scales. This would offer an approach to comparing and possibly aligning policies such as the diverse set of laws and strategies aimed at regulating resource use. These vary considerably in terms of scale, scope, and objective, but also with respect to the point of time of their issuance and the envisioned time frame for action (e.g. Bundesministerium für Wirtschaft und Technologie (BMWI), 2010; Commission of the European Communities (EC), 2008; Northwest Territories Department of Industry Tourism and Investment (2013)). In the process towards sustainable chemistry, a diversity of times is also related to new scientific insights, such as (i) innovative routes of syntheses using new resources more prudently, (ii) the application of the benign-by-design principle (Leder et al., 2015) for new molecules, materials and products, and (iii) thinking in new business models like chemical leasing.

5.2.2 Find windows of opportunity

Measures towards sustainable chemistry or the use of metals are at all times taken within a broader context. An intervention in one system might result in intended or unintended effects in other systems or on different temporal and spatial scales. Employing a times perspective can enhance our understanding of how single factors and events relate to one another from a temporal perspective. Considering and comparing intervention measures over time, therefore, reveals a more profound image of the relation of an intervention and its effect. From a temporal perspective questions arise not only with regards to which factors might influence resource availability, but also when and for how long they influence it. It allows for the identification of *windows of opportunity* (i.e. the right time for action or decidedly non-action; *kairos*), considering the interplay of several factors, each with their own inherent time scales and rhythms. Defining windows of opportunity should be based on a thorough system analysis that includes an enhanced understanding of the involved rhythms, time scales, and patterns of change. To give an example, the processes of learning and behavior change associated with the establishment of new (business) practices can be very long. This is because patterns of behavior will often persist despite constantly increasing information flows in terms of both amount of information and speed of dissemination, which have a potential influence on people's opinion. Behavior change involves perceiving and understanding, arriving at some degree of familiarity with a certain issue, and finally being able to act accordingly. Meanwhile, a gap between knowledge and action is created that needs to be overcome (O'Brien, 2012). Replacing established world-views may, for instance, take a generation or more, and the necessary measures may seem counterintuitive at first. This is especially the case for behavior that is driven by particular interests such as economic growth, as Meadows (2008) elaborates with regards to the issue of leverage points. Processes targeting a paradigm change may take longer, but may also entail more profound change (Abson et al., 2016; Meadows, 1999). An example would be chemical leasing, which implies a profoundly different understanding of doing business in the field of chemical use.

5.2.3 Build long-term strategies with precaution

A long-term precautionary approach to chemical development, implementation and use has several practical consequences on what is to be considered practical, safe, or innovative. An intervention option that appears attractive and appropriate at first sight might turn out to have unintended consequences in the long run. One example is the dissipation of metals due to a higher material diversity in modern technological devices, which resulted from increased material efficiency. Dissipation and limitations to recycling are therefore unintended long-term effects of an unsuitable degree of *efficiency* (Kümmerer, 2016). Similarly, rebound-effects result in higher absolute use of resources despite a smaller concentration within each device (John et al., 2016; Wäger et al., 2012). Following the precautionary principle would mean to demand feasible recycling procedures prior to allowing a small-scale use of metals in electronic and other devices. Product innovation cycles and pace, consequently, are governed from the end-of-life perspective rather than from design or production. In addition to that, actions need to be identified and avoided that might pose health or environmental hazards (through bio-accumulation of dissipated materials), as long as their non-harmfulness is not proven. Considering that this might be hard to accomplish in the light of ever new materials and resulting toxicities, it calls for increased action to minimize dissipation. It might be said that such reasoning could inhibit innovation. We argue, however, that it would rather shed a different light on what is considered *innovative*, and would in the long run improve product design and other (technological) processes. Limitations have often proven to spark innovation. As an example, take-back obligations for the producer or designer of products would serve as an incentive to design products in a way that makes them easier to recycle. Actual prohibitions of products can be avoided by allowing intermediate solutions such as a comprehensive collection and storage of end-of-life products, until economically feasible recycling procedures have been established. This is already an established procedure in the Swiss Canton of Zurich, where phosphorus is to be stored in a way that allows for a later retrieval (Amt für Abfall Wasser Energie und Luft, 2016). Based on this, long-term precaution in and with chemistry would also reduce the temporal and spatial extent and dynamics of substance, material and product flows, as well as their compositional heterogeneity. It needs to take into account the limits of recycling based on its timescapes, e.g. the product life cycle, product use and product life time, the point of time and the dynamics of its market introduction and recollection, or the time for the development and establishment of an appropriate recycling technology. The prudent consideration of the times connected to recycling cannot overcome the limitations set by thermodynamics, but allows us to come closer to these limits. In retrospect, long-term precaution could have helped to avoid (or at least reduce) negative outcomes that affected the image and trust related to a company or the discipline as a whole in the public (e.g. POPs, micro-plastics, flame retardants, endocrine disrupting chemicals, or severe accidents like Bhopal and Schweizerhalle).

5.3 Lessons learned and their implications for the future

Research, policy-making and industry can profit from integrating temporal aspects into system understanding and decision-making processes in chemistry and resource use in several ways. This should include an acknowledgement and operationalization of (inter alia) the following points:

1. **Disturbances might become visible at another (spatial as well as temporal) scale or in another time and place than possibly expected.** This means that

modes of observance have to be constantly revised and adapted to consider potential delays and varying perception. Mechanisms should be installed that allow for a rather quick reaction to (unexpected) disturbances. With regards to this, we have mentioned the examples of CFCs as well as persistent organic pollutants. Both are applied locally, but distributed globally, which implies long-term presence and effects, such as the ozone hole and a contribution to climate change in the case of CFCs. More recently, examples of uncertain impacts on humans and the environment include pharmaceuticals in the environment and the mobilization and dissipation of rare earth metals. Accordingly, the management of chemical production and use must acknowledge that effects in complex and highly interconnected systems often cannot be fully anticipated. Systems must be built with enough flexibility (and thus resilience) to absorb shocks from unexpected changes and impacts, including those from other scales, times, and different fields of action.

2. **Point of time and duration determine the consequences of an event.** This includes its beginning, the moment it induces changes at a specific rate, the period of time it is active, and finally the moment it ends. In that context, the same degree of disturbance might either originate from a single, more severe event (*= point of time*) that might be easily noticeable, or from a long-term exposure to a certain threat (*= time line*) that might not be as easily observable. We must therefore understand an event's duration, its temporal impact (how long does it and its aftermath last?) and its force to be able to anticipate the extent of possible adverse effects and their times. Drawing back upon the example of CFCs, this observation emphasizes the significance of existing or non-existing windows of opportunity for legal and political intervention and the point of time of political action. Governance, especially in the case of such complex interactions as in chemical production and use, must reflect the long duration of political decision-making processes as well as the fact that in many cases a conventional scientific cause and effect relationship cannot be established.

3. **Natural systems are characterized by rhythms. These offer some degree of freedom or variance, making them rather adaptable and adaptive within a certain range.** The resulting flexibility increases a system's resilience. One can – and

> chemistry as well as resource use in general should – thus learn from nature's flexibility for the design of actions, policies and other interventions into natural as well as socio-technical systems in order to be more resilient to disturbances. This holds true especially for (resource) strategies, since these considerably contribute to shaping future actions, exist on various spatial scales and in different regulative contexts, and often highly vary in their thematic scope and time frame.

Further elaboration is needed on how actors' responsibility is determined in complex systems with large temporal and spatial scales and big time lags. In these systems, a potential hazard often has not one single cause or one specific source. It is rather created through the interplay of various factors or originates from the normal mode of operation rather than from a disturbing event.

To contribute to such an elaborated understanding of the manifold factors and their inherent times, research will have to bring different disciplines together (Kümmerer, 1996) and thoroughly engage with practice to build a comprehensive picture. The *Stoffgeschichten* concept could support such inter- and transdisciplinary approaches and could prove to be valuable to bringing time into our considerations for sustainable chemistry and metal use (Achzet et al., 2010; Böschen et al., 2004; Dießenbacher and Reller, 2016; Huppenbauer and Reller, 1996). The concept aims at bringing together all relevant aspects throughout a product's or technology's life cycle, including sociocultural and political factors (Böschen et al., 2004). The approach makes the temporal dimension explicit in the narrative for a specific material or product. It can thus shed a different light on potential solutions and the scope of action.

The information and views presented here have also demonstrated the importance of observing systems not only from various spatial scales, but also within appropriate time frames. However, as Bergmann et al. (2014) state: "Research on sustainability issues is normally conducted within project periods of three to five years – largely as a result of the terms and conditions of program funding. Documenting and developing transformation processes, however, requires a much longer perspective." Achieving a better understanding of the interface of time, space, knowledge, and action must not only be based on a more profound understanding of the involved times and their interactions. It is equally important to monitor and assess processes over an appropriate period of time to really grasp change and potentially measure progress towards sustainability. This puts time and temporal diversity – in close relation to space – more into the focus of transformative and transformation research; not only for sustainable chemistry and resource use, but for all research and action taken on the grounds of contributing to sustainability. Such integration provides a profound base for understanding system's dynamics over the long-term. Moreover, incorporating an explicit understanding of time supports a more solution-oriented, practically-applicable approach to comprehensively designing interventions into these systems. It contributes to bridging the gap between analysis and assessment on the one hand and appropriate strategy building, even in the light of uncertainty, on the other (John et al., 2016; Wiek et al., 2012).

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4.2 Acknowledging temporal diversity in sustainability transformations at the nexus of interconnected systems

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Abstract

The language of the global sustainability discourse in science and society is laden with time rhetoric, and time has been identified as one major contextual condition for sustainability transformations. Still, time and temporal dynamics are often not explicitly considered or conceptualized in research and strategy building towards sustainability transformations in social-ecological and socio-technical systems: While existing approaches to time such as the concept of time ecology mainly inform system knowledge, many transformation concepts are found to lack an in-depth integration of time. This sets up the challenge to acknowledge and operationalize temporal system dynamics in transformation processes, in order to be able to plan and act purposefully towards long-term sustainable development. In this article, we take a first step to meet this challenge and propose an approach towards operationalizing and integrating the findings of time ecology for these sustainability transformation concepts. The presented time-in-transformations-approach consists of three subsequent steps. Each step informs specific features of the transformation process and is operationalized on the basis of insights from time ecology. By applying these steps to the exemplary case of the mineral-energy nexus, we show how our approach might enable a better temporal system understanding and support a structured reflection on human perception of change and typical temporal patterns. The approach leads to two main outcomes: First, it can inform how to design and carry out interventions in a way that they consider a system's temporal resilience and transformability. Second, an active consideration of temporal dynamics can inform strategy building towards coherent sustainability transformations across sectors and regulatory levels, spatial and temporal scales. Therefore, it can contribute to a shared and operational understanding of temporal diversity and may thus meaningfully complement existing approaches to analyze, assess and purposefully intervene into systems across sector boundaries.

1. Introduction

1.1 Relevance

The language of the global sustainability discourse in science and society is laden with time rhetoric (van der Leeuw et al., 2012). Climate change mitigation calls for *immediate* action to avoid *long-term* adverse effects (COP 21, 2015; Stern, 2006). The dynamics of *ever-faster* growing impacts of human activities on the earth's system are framed as "The Great Acceleration" (Steffen et al., 2015). Goals have been set for *specific time horizons* such as 2020 (e.g. the two-degree climate mitigation goal (COP 21, 2015), 2030 (Sustainable Development Goals (United Nations, 2015) or 2050 (energy strategies (IEA, 2010; IRENA, 2014). Finally, already the Brundtland report (WCED, 1987) states that activities fostering a sustainability transformation need to be designed with a *long-term* perspective for generations to come. Despite this omnipresence of time-related language, time is often not explicitly integrated in the sustainability debate, neither in research nor decision-making and the public discourse (Held, 2001). Acknowledging this, Reisch and Bietz (2015) emphasize the significance of time and temporal elements for sustainability transformations. The authors present time and temporal elements as boundary condition and potentially powerful design variables for more sustainable lifestyles. Although scholars have identified these and other general time-related patterns of transformation processes, they are not (yet) embedded in a coherent theory (Olsson et al., 2014). Time is touched upon as a factor in transformation research, and the need for transformation is touched upon by time research. Yet both approaches are not explicitly linked in a way that allows to straightforwardly consider temporal aspects to inform decision-making and planning in a way that fosters transformations towards sustainability.

1.2 Motivation

The need for an explicit consideration of time is very apparent in the discourse on the transformation of the resources and energy sectors: Time horizons of interconnected processes behind resource and energy use range from short-term supply bottlenecks to the long-term needs of safely storing nuclear waste. We believe that a long-term perspective alone will not suffice to address future challenges at this *mineral-energy nexus* (Giurco et al., 2014). Rather, it must be assured that plans in both sectors are (temporally and spatially) aligned to plan and act purposefully towards long-term sustainable development. This calls for an explicit in-depth integration of temporal aspects in research and actions towards sustainability transformations.

1.3 Contributions

We postulate that a more explicit approach to temporal diversity could considerably enhance our understanding of transformation processes in highly interlinked systems. Beyond this, we could also make use of this more differentiated perspective on time to purposefully intervene into systems across sector boundaries. Time ecology as one of the most prominent examples of a more explicit and diverse approach to 'time' appears to be very helpful to elaborate on this issue because it emphasizes the temporal dimension and diversity of temporalities in understanding systems (Adam et al., 1997; Clancy, 2014; Held et al., 2000; Hofmeister, 2002; Kümmerer et al., 2010; Kümmerer and Hofmeister, 2008). In this paper, we analyze the practical relevance for and means of applying principles of time ecology to the sustainability transformation of interconnected systems, and discuss how a deeper and more explicit understanding and consideration of time in that sense can contribute to (i) improve our understanding of the dynamics behind such connected systems and related transformation processes and to (ii) assist designing interventions into complex and highly connected systems to purposefully navigate sustainability transformations.

1.4 Organization of the paper

Fig. 1 illustrates how the paper is organized and how the sections build on each other. At its core, we suggest the three-step time-in-transformations-approach that aims at developing an enhanced temporal perspective on processes of change across system limits. Each step relates to one of three key requirements (R1 to R3), which we identified in a survey of two bodies of literature: time (A) and transformations (B). To illustrate its potential practical relevance, we apply the suggested approach to exemplary processes at the mineral-energy nexus, namely the case of metal and renewable energy use. Following the logic of the three steps, we sketch out how the approach may inform decision-making and strategy design. We then synthesize our findings and reconnect them to both the literature on time and on transformations. Our key findings relate to the benefits we could gain from integrating the two mutually supporting perspectives on time and transformations for both understanding and purposefully intervening into systems.

Throughout the paper, we use the following terminology: (i) **temporal features** as technical term to differentiate between characteristics of time such as point in time, duration, or time lag; (ii) naturally occurring **temporal patterns** within a system such as the development of vegetation over or with the seasons; (iii) **interventions** into systems that notably disrupt and alter these temporal patterns; (iv) the overall sustainability **transformation** of a system, understood as a fundamental structural change towards a more sustainable state.

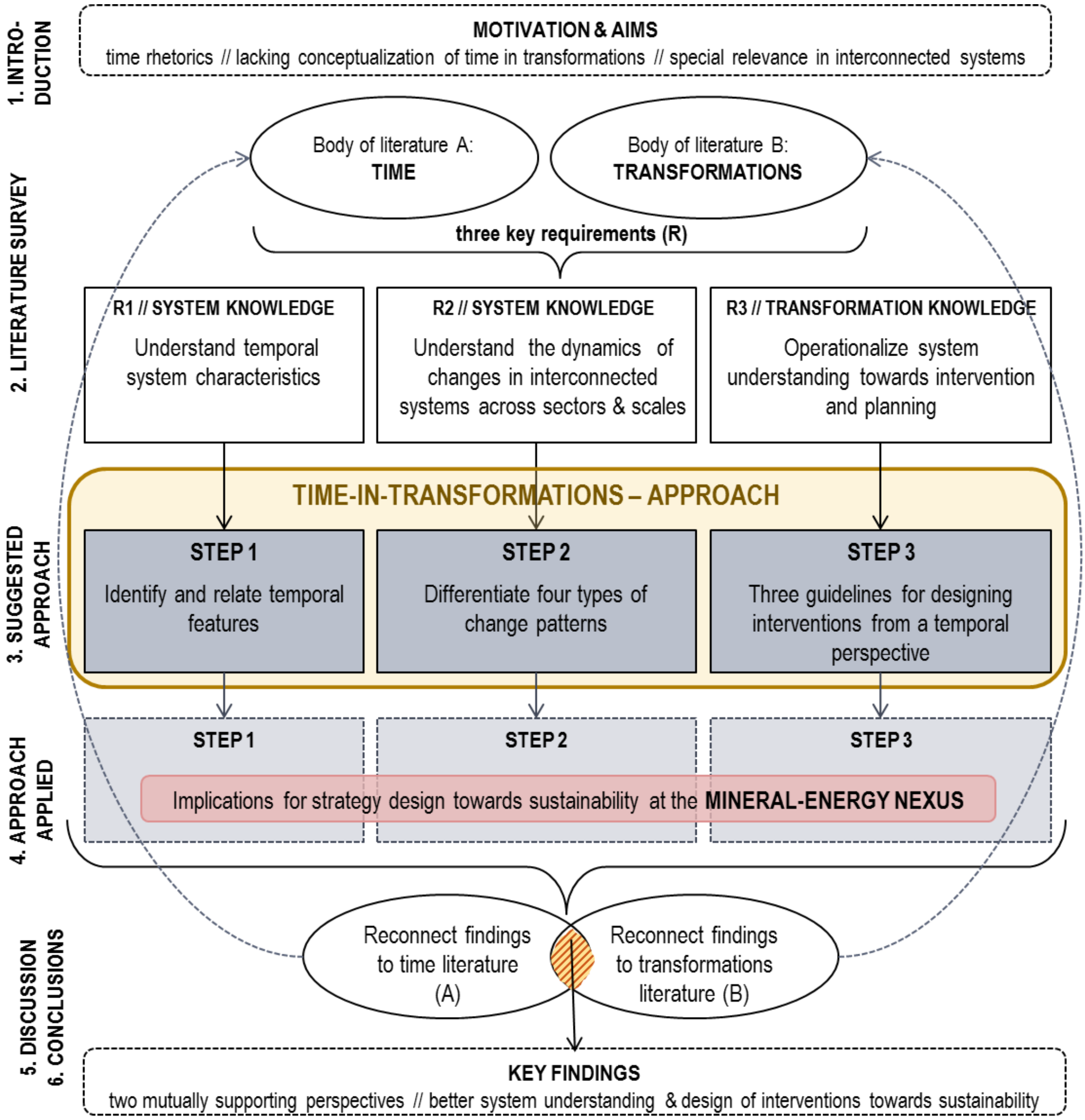

Fig. 1: Schematic overview of the paper. A literature survey of two bodies of literature results in the definition of three requirements for a deeper understanding of time in transformations. We present the three-step time-in-transformations-approach that responds to each of these requirements and apply the suggested approach to the mineral-energy nexus as an exemplary case of a highly interconnected system. We reconnect our findings to the two respective bodies of literature and extract key findings relating to the positive effects of an increased conceptual integration of time and transformations.

2 Literature survey on time and sustainability transformations

We applied the general principles of a snow-ball search to survey the two bodies of literature of time and transformations, using Scopus and Google Scholar. For time literature, we focused on the time ecology approach to emphasize the aspect of temporal diversity. For literature on transformations, we focused on two of the most prominent approaches. In the following, we sum up our main findings with regards to aspects of transformation in time research (section 2.1) as well as aspects of time in transformations research (section 2.2), concluding with three key requirements for a closer integration and consideration of the two bodies of literature (section 2.3).

2.1 Time ecology and transformation

The time ecology concept understands 'time' as one major characteristic of a system (Kümmerer et al., 2010). It touches upon vital aspects of sustainability, but does not formulate a clear objective of actively inducing transformation processes towards sustainability. 'Time' is to be considered more diversely than in the purely quantitative, 'Newtonian' sense of time which is closely related to clock time and reversibility (Kümmerer and Hofmeister, 2008). Time measures are considered to have a descriptive and a normative component. The normative component refers to making proper use of time, and to finding the 'right' pace and point in time; it describes the right time for action as 'kairos' (Adam et al., 1997). Sustainable development is seen as an 'inherently temporal concept' (Held, 2001) with reference to future generations' own needs. A major objective is seen in finding suitable time measures for human action towards their environment. An explicit and integrative temporal perspective is considered necessary to understand how ecology, economy, and society interlink (Held, 2001). One example for a more explicit link of time ecology principles to governing system change is the temporal misfit approach. It states that systems may be irreversibly disturbed whenever the inherent system times or other temporalities of two or more coupled systems do not align, or when the speed of occurring change is inconsistent with the maximum possible adaptation rate of a system (Held and Kümmerer, 2004). As an example, temporal misfits may be created when regulative action is taken at the wrong time (i.e. too early or too late) or otherwise irrespective of the time frames or adaptation rate of the natural system. Munck af Rosenschöld et al. (2014) have identified a number of temporal misfits in the governance of endocrine-disrupting chemicals (EDC) such as between the production of new knowledge and the emergence of new impacts and adverse effects, or the 'cycles of regulation and impacts' (p. 6). Also, the point of time of an intervention is considered crucial for temporal fit (Kümmerer and Hofmeister, 2008).

2.2 Transformation research and time

Several theories, concepts and methodologies related to transformation research and the normative guiding idea of sustainable development have been developed over the last years. They share the objective to analyze or find appropriate pathways to tackle unsustainable trends in often complex human-environment systems and act towards long-term sustainability (Luederitz et al., 2016), but may relate differently to time as such. In the literature on sustainability transformations and in related fields, transformation processes are understood to be context-specific developments that happen over a specific period of time. Two prominent approaches and how they consider temporal aspects are introduced here: transitions of socio-technical systems (STS) (Grin et al., 2010) and transformations of social-ecological systems (SES) (Walker et al., 2004).

Socio-technical transitions theory has mostly been applied to individual sectors such as energy or health. The transition of a STS in time is described as a sequence of four alternating phases: (1) pre-development, (2) take-off, (3) acceleration and (4) stabilization. The ideal-typical transition process is conceptualized as s-shaped curve (Geels et al., 2016; Rotmans, 2001; Rotmans and Loorbach, 2010). Transition processes depend on a variety of contextual factors (Geels and Schot, 2010, p. 26), which potentially open a 'window of opportunity' that facilitates change (Geels, 2005, p. 685). This enables radical innovations to influence the system. Once triggered, major changes may occur within short time frames, which will then lead to a new regime configuration or to the collapse of the system (Göpel, 2016).

SES are perceived as complex and adaptive to internal and external influences. They are characterized by the capacities resilience (constantly changing yet remaining within critical thresholds), adaptability (adjusting to external and internal changes yet remaining in the current trajectory), and transformability (crossing thresholds into new development trajectories) (Folke et al., 2010). SES undergo a process of constant evolution, in which the speed of change varies considerably (Gunderson and Holling, 2002). Actively induced transformation processes of SES pass three main phases: (1) preparing for transformation, often at different scales of the social-ecological system and by different actors at the same time; (2) navigating the process step by step; and (3) building the resilience of the new system state, where several factors (such as leadership, funding and legislation) have been identified as helpful. Often, the first and second phases occur in a window of opportunity (Olsson et al., 2014, 2006, 2004).

Both approaches share a rough differentiation of three phases: (i) preparing system change, (ii) actual intervention and occurring change, and (iii) stabilizing the new system state. Both approaches mention that time may run unevenly or speeds might be very different in the course of transition or transformation processes (Göpel, 2016; Gunderson and Holling, 2002; Rotmans and Loorbach, 2010). Still, both do not explicitly consider this temporal diversity. In the following, we use the terms *(sustainability) transformation* and *transformation research* for both approaches introduced above.

2.3 Three requirements to support a deeper understanding of time in transformations

At present, the two bodies of literature evolving around temporal diversity and transformation are mostly treated separately. While the time ecology concept presents the temporal dimension as a valuable system component, it does not provide sufficient detail on how to apply this understanding to conceptualizations of transformation processes or to designing interventions into systems. Similarly, while transformation research provides some starting points in this respect, time is mostly neglected as a vital system component. We identified a need for understanding temporal diversity in systems under transformation, approaches to deal with different temporal and spatial scales across interconnected systems, and practical knowledge on how to design interventions in coherence with this understanding of temporal diversity. In order to overcome this gap and make full use of an improved and applicable understanding of temporal diversity in processes of or towards sustainability transformations, we therefore suggest addressing the following three requirements:

- (R1) knowledge regarding the temporal system characteristics (i.e. understanding its components from a temporal diversity perspective),
- (R2) knowledge with respect to the point of intervention and the potential dynamics of (desired and undesired as well as intended and unintended) changes in interconnected systems across sectors and scales (i.e. when and where to intervene to reach the desired outcome), and
- (R3) knowledge in the sense of an operationalized system understanding towards intervention and planning (i.e. how to intervene in awareness of the temporal specificities of the systems).

While R1 and R2 target an improved understanding of system characteristics (*system knowledge*), R3 relates to the creation of knowledge that can be used to achieve progress or change behavior (*transformation knowledge*) (see (Brandt et al., 2013; Wiek et al., 2006) for the differentiation of knowledge types used in this study).

3 A three-step approach to integrate time in governing sustainability transformations

The three-step time-in-transformations-approach presented here aims at integrating and operationalizing the concept of time ecology (Adam et al., 1997; Held et al., 2000; Kümmerer and Held, 1997) with transformation research (Grin et al., 2010; Gunderson and Holling, 2002). As illustrated in figure 2, each step responds to one of the key requirements identified in the literature survey (section 2.3) and may inform one or several of the three main phases of transformation processes identified in section 2.2. The steps are subsequent and thus either form the basis for or inform the following one. While step 1 and 2 enhance system understanding and prepare for the intervention (*where and when*), step 3 informs the intervention itself (*how*). Step 1 leads to a temporal system understanding that may inform the preparation phase (phase 1) of transformation processes. Step 2 differentiates patterns of change and may thus inform the actual point of intervention (phase 2). The guidelines presented in step 3 may contribute to navigating the actual change process (phase 2) and thus indirectly support the process of stabilization (phase 3).

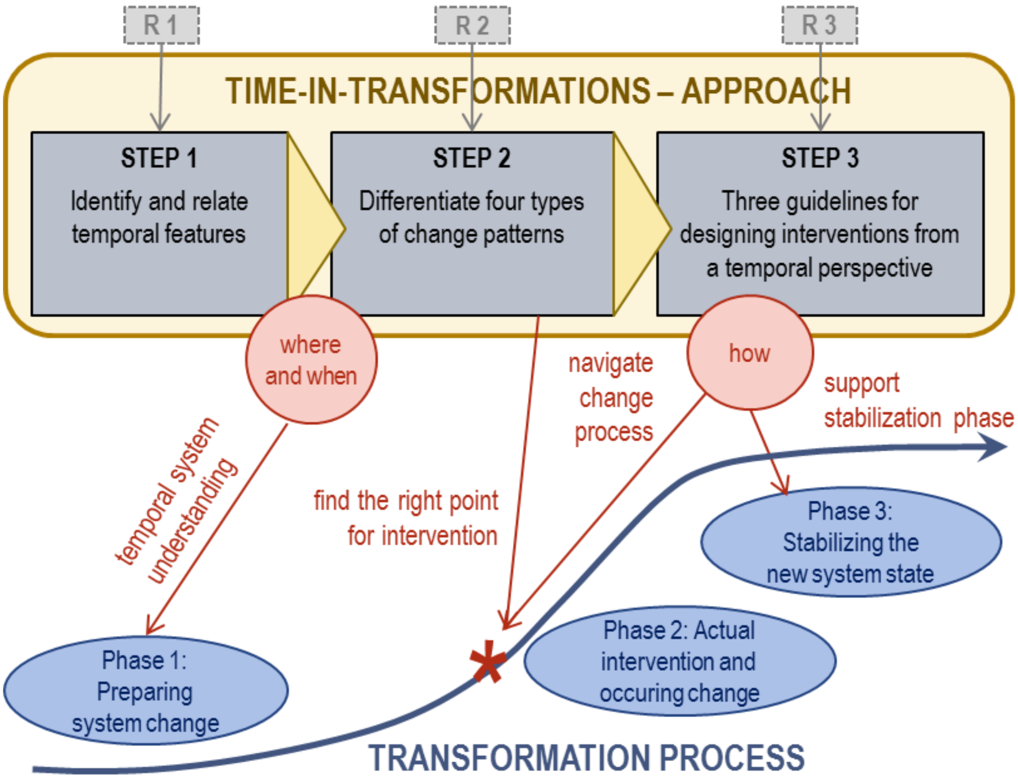

Fig. 2: Interrelations of individual steps of the suggested time-in-transformations-approach and phases of the transformation process (approach with the three steps in yellow and grey, shared phases of transformation processes in blue, arrows (red) indicate how each step may inform one or several phases).

3.1 STEP 1: Identify and relate temporal features

AIM	Get an overview of the observed system(s), their temporal specificities, and defining components in terms of system dynamics. We suggest differentiating between the natural, the socio-technical and the regulatory spheres. The natural sphere encompasses natural processes such as ecosystem dynamics. The socio-technical sphere includes processes related to mainly economic activities such as mining, production and consumption, while the regulatory sphere encompasses processes related to governance and intervention measures such as policies and legislation. Step 1 also allows to consider several sectors that may be involved in an intervention.
APPROACH	Following the time ecology principles, systems or system components are usually characterized by a combination of several temporal features. These are constituted by the basic temporal elements point of time and timeline. In combination with the basic temporal relations ‘before’, ‘after’, and ‘simultaneous’, they allow for statements being made on, among others, the direction of time, temporal extension, time scale, duration and change, or the unique times of past, present, and future (Kümmerer et al., 2010). Time exists as a variety of different temporal features with

strongly differing characteristics (Adam et al., 1997; Held, 2001; Held and Kümmerer, 2004; Kümmerer, 1996; Kümmerer et al., 2010).
Fig. 3 below lists and describes these temporal features (Kümmerer et al., 2010). Use this list to identify the relevant temporal features of the observed system for each sphere and sector. Take a temporally-focused perspective on the system to identify path dependencies or temporal elements that are necessarily sequential.

ADDED VALUE

The identification of the variety of temporal features inherent in a system is a necessary basis for an enhanced system understanding. A common consideration of all involved sectors provides a suitable basis for the identification of system features and underlying dynamics that might have an influence across sectors' limits. Action towards increasing sustainability in and across these sectors will have to consider all relevant temporal features and their interlinkages. In that respect, this step can complement system analysis and emphasizes a process-oriented perspective.

duration	*'time scale specific for an organism, population, system, and/ or process' (Kümmerer et al., 2010); informs 'how long an event, or its influence, lasts' (Kümmerer, 1996)*
point in time	*the specific 'moment when an event occurred' (Kümmerer, 1996), incl. non-regular events; this has an 'influence on the effects of that event' (Kümmerer, 1996); 'crucial for the development of a system: points in time when a system or organism is sensitive and insensitive to external input or change' (Kümmerer et al., 2010)*
rhythm	*'recurrence of the similar with variation, synchronized between processes and systems' (Kümmerer et al., 2010)*
metronomic beat	*'exact time scale and point in time: repeating the same action; intended to be invariant and uniform' (Kümmerer et al., 2010); there is no metronomic beat in nature (Kümmerer, 1996)*
speed, acceleration, deceleration	*this dynamic conduct of a process is 'important for a system´s reactions on disturbances, problematic if not adequate' (Kümmerer et al., 2010)*
timing	*'coincidence and / or synchronization of events and processes' (Kümmerer et al., 2010), may be intended or not*
time lag	*'delayed damage or incomplete development; masking of time-related effects' (Kümmerer et al., 2010); a triggered process may run over some time before the effect can be perceived*
temporal webs	*'interplay of different time scales and points in time within systems and different systems and levels' (Kümmerer et al., 2010)*

Fig. 3: Terms and definitions to help navigate the identification of relevant temporal features of the observed system (as compiled by Kümmerer et al. (2010) (a) for the case of soils and (Kümmerer, 1996) (b))

Systems have very specific *Eigenzeiten* (inherent times) such as naturally occurring temporal patterns (Adam et al., 1997; Held and Geißler, 1995). These system-inherent times are embedded within organisms and ecosystems, but also non-biotic processes. Rhythms, for example, allow a system temporal flexibility and elasticity, which is a precondition for its resilience (Held and Kümmerer, 2004; Kümmerer et al., 2010). It is necessary to acknowledge a system's inherent times when planning an intervention into a system to avoid (temporal) misfits, but also to take advantage of their flexibility and the resulting resilience.

3.2 STEP 2: Differentiate four types of change patterns

AIM	Develop an understanding of underlying patterns of change and the degree of flexibility the system(s) at hand offer(s). This helps to make full use of 'windows of opportunity' and to determine promising entry points for intervention. Understand not only the inherent system times, but also the underlying processes and temporal patterns of constant change (intended as well as unintended), including 'naturally' occurring disturbances (Held and Kümmerer, 2004), to be able to determine where to rely on observations of the system and foresee or predict future behavior.
APPROACH	Identify and categorize system-inherent patterns of change to determine whether or not it is possible to observe or predict what is happening. Patterns are formed by specific points of time and time lines that result in a certain temporal irregularity and temporal extent. (Relative) Temporal irregularity describes how regular or irregular changes in a system are, ranging from the rigid metronomic beat to highly irregular specific points in time (events). (Relative) Temporal extent describes the time it takes for the according system element to change, which ranges from split seconds to millions of years and is defined by the time covered between specific starting and ending points. This results in four types of temporal patterns of change as described below.
ADDED VALUE	The step adds to understanding the dynamics and interactions of changes in systems and enables a more directed view on interplays and mutual reactions between different spheres and sectors. It helps to differentiate system-inherent patterns of change from on-going transformational change and allows estimating how long it might take until impacts of interventions become visible. It may sharpen the focus on features that may (unintendedly) trigger a development into an irreversible new state and thus need special attention.

We suggest that the following temporal patterns can be differentiated:

- *Type 1 temporal patterns* are short- to mid-term intervals of change with a low to medium temporal irregularity, i.e. they have a relatively regular pattern. Examples are day and night, regular maintenance intervals to keep machines in order, or legislative periods in politics. Here, changes are relatively easy to observe and predict.
- *Type 2 temporal patterns* are mid- to long-term changes, with a low to medium temporal irregularity. Examples include solar and lunar eclipses, but also the anticipated average lifetime of technical devices such as power plants. Changes here, or the temporal pattern itself, are possibly harder to observe, but, once recognized, rather easy to predict due to their relative regularity.
- *Type 3 temporal patterns* characterize changes that are mid- to long-term in duration and show medium to high temporal irregularity. Examples are the process of recognizing ozone depletion due to CFCs and the formation of ore deposits within geological time scales. It is rather difficult to observe as well as to predict changes occurring here.
- *Type 4 temporal patterns* characterize shorter, or abrupt, change, with a medium to high temporal irregularity: One example occurring in nature would be the eruption of a volcano; in the context of the mineral-energy nexus similar patterns can be found in the volatility of resource prices. Such events may be rather easy to observe for humans, but are very difficult or impossible to predict.

The types strongly relate to the fact that the spatial and temporal scales of an observed system influence the time it takes to perceive some kind of change or disturbance (Held and Kümmerer, 2004; Kümmerer, 1996). Changes in larger systems are often observed much later than those in smaller systems, which emphasizes the close relation of spatial and temporal scales (Gibson et al., 2000). A perception lag might cause considerable delays before action is taken (Adam, 1998; Held, 2001; Kümmerer et al., 2010). Also, it is important to differentiate between the time it takes to recognize a specific change process for the first time from the temporal patterns the change process itself might have. For example: It took several decades to detect and understand the process of ozone depletion, but we can now observe and deal with annual variations of ozone depletion, i.e. changes that are rather short-term and relatively regular. While the former would be categorized as type 3, annual variations of ozone depletion would thus be categorized as type 1.

Whether or not a specific system feature may be an appropriate entry point for intervening into the system also depends on the degree to which it can be influenced by humans. This relates to two (temporal) factors. First, the less predictable a change process is, the more difficult it is to intervene at the right point in time and influence the system according to the desired outcome. Second, the time scales might just be too long to be influenced from an individual human perspective. With regards to changes that are both irregular and on long time scales, interventions in the system must be flexible enough to adjust to this irregularity and must not overstretch the system's capacities to restore.

3.3 STEP 3: Guidelines for designing interventions from a temporal perspective

AIM	Design and plan interventions into a system in a way that does not cause irreversible harm but instead contributes to the desired transformation of a system, which can also support the stabilization phase and build resilience.
APPROACH	Apply general guidelines for the manner in which an intervention should be executed. Based on the principles of time ecology, three overall guidelines may be formulated that respond to the interconnectedness in temporal webs and the need for coherence with the limits of temporal flexibility, and are informed by an in-depth understanding of the relations of temporal and spatial scales (see Table 1).
ADDED VALUE	Following these guidelines can inform the manner in which to carry through such an intervention. With increasing relevance and need to act towards sustainability across sectors, this may support policy making especially in complex environments, helping to incorporate temporal diversity into actual planning and practice.

Applying the following guidelines (Table 1) has particular relevance with regards to the different spheres and the regulatory level or spatial scale at which an intervention is taken. Interventions usually target a specific sphere of a system. The Paris Agreement following COP21 and the Montreal Protocol, for example, both aim to intervene into the national regulatory spheres of their member states. As response to these international treaties, national governments intervene into the socio-technical sphere with the aim to reduce greenhouse gas or ozone-depleting emissions, respectively. The guidelines of step 3, based on the temporal system understanding gained in steps 1 and 2, enable decision-makers to place interventions deliberately in the targeted sphere. Moreover, the guidelines may help to minimize negative impacts in spheres that should remain undisturbed.

Table 1: Guidelines for designing interventions.

Target	Approach & background	Conceptual basis
Avoid temporal misfits	*Acknowledge the diversity of temporal features in a system & engage proactively to suit the purpose* Temporal elasticity is limited and an intervention into a specific system might change its temporal characteristics. Including time into our thinking and action must therefore be informed by an understanding of the underlying temporal webs and the limits of a system's temporal elasticity and should aim for harmonization of times within these limits. Working at the nexus of two or more sectors creates even more complex temporal webs and increases the danger of misfits. It demands foresight and thoughtfulness to consider the relevant times of all system components into the design of an intervention, and to use this knowledge so that the intervention ensures functionality and follows the intended purpose. *relevant temporal features*: temporal webs, duration, speed - acceleration – deceleration	time ecology (cycles, frequencies, rhythms and their mutual relation) (Kümmerer, 1996) timescapes (Adam, 1998) environmental governance (misfits/ mismatches approach) (Dille and Söderlund, 2011; Munck af Rosenschöld et al., 2014; Pahl et al., 2014)
Minimize negative impacts	*Find the right point in time to remain within or even improve a system's (temporal) elasticity.* Irregularly occurring changes might challenge the stability of a system more than regular ones, since a system may adapt or even rely on regular change, but might not be 'prepared' for irregular events. The temporal patterns at the nexus of two or more sectors may leave room for only small windows of opportunity for action within the systems' temporal elasticity. *relevant temporal features:* timing, point in time, rhythm	time ecology (flexibility of a system, temporal impact assessment) (Held and Kümmerer, 2004; Kümmerer, 1996)
Acknowledge or reduce delays	*Consider the role of context for the perception of change.* Temporal and spatial scales are related, and perception and reaction may be slower in larger systems. The perception of the present situation in relation to the past and future might be influenced by the position, power and experience of a decision-maker, and might thus also differ depending on the sector one works in. This guideline aims to reduce delays in the perception and management of processes. It must be acknowledged, however, that delays in natural systems can also often be understood as buffers that slow down negative effects and leave time to maneuver. *relevant temporal feature:* time lag	time ecology (timescapes: 'to regain a sense of context'), psychological research (perception and delay) (Adam, 2004, 1998; Pahl et al., 2014)

4 Applying the time-in-transformations-approach to the case of the mineral-energy nexus

As shown in section 2, bringing time and transformation together is not just a question of defining short-, mid- and long-term objectives. To illustrate the added value of the explicit integration of time and temporal diversity, we applied the three-step approach to interventions towards sustainability in the interconnected sectors of metal use and renewable energy use.

Transformation processes can neither be understood nor guided properly by treating systems or sectors as separate entities, as it is currently often the case for actions taken to achieve a more sustainable resource and energy use. Both are 'inextricably-connected' and 'overlap[ping] with bidirectional influences' (Giurco et al., 2014). Generally, strong interlinkages make it difficult to oversee all system components and interactions of cause and effect can often not be easily distinguished (cf. e.g. Held and Reller, 2016). Most literature on mineral and/ or energy futures does not yet sufficiently address nexus issues (Giurco et al., 2014) and time is either largely disregarded or incorporated very differently. In resource (availability) estimates and depletion studies (Angerer, 2010; Graedel et al., 2015; Tilton, 2002), time mostly plays an ancillary or implicit role. Some practical approaches such as visioning and foresight explicitly take on a future perspective within a certain time frame (Prior et al., 2013). Often the time frames of studies cover not more than a decade, which will have to be considered as too short to adequately address the challenges of sustainable mineral resource use (Giurco et al., 2014). Compared to that, energy studies such as scenarios or models often take a longer perspective of several decades (ECF et al., 2010; IEA, 2016; IRENA, 2016).

In the following, we focus particularly on neodymium production and use as an illustrative example. Neodymium is a rare earth element (REE) that is needed for many renewable energy technologies such as high-strength permanent magnets in wind energy converters (Graedel, 2011; Nansai et al., 2015; Zimmermann et al., 2013). It ranks high among (especially short-term) criticality ratings and supply bottleneck estimates (Commission of the European Communities (EC), 2014; Moss et al., 2011; US Department of Energy (DOE), 2010) and is even considered to potentially delay broad-scale wind power implementation, even though supply would eventually cover risen demand (McLellan et al., 2016).

4.1 STEP 1 applied: Temporal features of metal use and use of renewable energy technologies

Relevant temporal features of the transformation process towards sustainable energy and metal use are compiled in table 2. It illustrates the temporal diversity that ought to be considered and reveals the large gap between the system-inherent time scales of resource and energy use within as well as across sectors and spheres. The inherent time scales of metal use are much longer than those of renewable energy use, and the phase in which the metals are used for generating renewable energy is extremely short in relation to the whole metal life cycle (see Tab. 2). This temporal imbalance between the metal life cycle and its in-use phase is aggravated by the fact that many rare earth elements (REE), including neodymium, are mined with radioactive elements such as thorium. The half-life of the most abundant Thorium isotope in nature (^{232}Th) is 14 billion years. In contrast, the preparation phase for generating renewable energy in a wind farm needs only months to a few years, and the life time of a wind turbine, which is also the in-use phase of neodymium, is 20 to 30 years.

<u>Implications for strategy design:</u> The different time horizons can be considered a major challenge for developing joint strategies that target a sustainable metal and renewable energy use. Relating the temporal features to one another helps to uncover sequential steps in a process, where a change in one would lead to a change in another. For example, less frequent maintenance (*rhythm*) might lead to a shorter overall lifespan (*Eigenzeiten/duration*) of a technological device.

Table 2. Temporal features of metal use in renewable energy technologies - the example of neodymium. Features are chosen according to Fig. 3. Sectors are indicated with "metal" for metal use and "RE" for renewable energy use

Temporal feature	Sectors	Example from the natural sphere	Example from the socio-technical sphere	Example from the regulatory sphere (governance, intervention measures)
duration	metal	time for formation of ore deposits, half-life of Thorium (is mined with Neodymium)	time needed for site development (mine/windfarm) or the development of recycling infrastructure	time needed for a new policy or legislation to be developed, agreed and implemented, possibly as a reaction to occurring change
	RE	period of specific wind conditions		
point in time	metal	eruption of a volcano (leading to copper mineralization via hydrothermal circulation)	specific moment for emission measurements of a mine	issuance of a new law, of new (regional) planning

	RE	solar eclipse	new turbine technology enters the market	
rhythm	metal	formation of sedimentary rocks	innovation cycles; market cycles (supply and demand); product life cycles	legislative periods
	RE	seasons: rhythms of global radiation intensity and wind	repowering cycles of wind turbines, regular maintenance	
metronomic beat	metal	- Not observed -	machines, e.g. in ore extraction	- Not observed -
	RE		generator frequency	
speed acceleration deceleration	metal	speeds of hydrothermal processes that lead to ore deposits	increasing speed of technological innovation and product life cycles	increase in amount of information available to digest and react upon prolongs overall reaction times
	RE	wind speed, tempo of weather times changes	inconstant wind speeds lead to fluctuating electricity generation	
timing	metal	availability of porphyry ore deposits at the surface: ores formed in the Phanerozoic and were subject to geologic processes since	collect materials on time for recycling; open new mine in time to react to increasing demand	issue a policy in accordance with others with which it interacts, e.g. EU raw materials initiative, national resource strategies
	RE	wind when electricity is needed	get biogas power plants running in time to even out fluctuations from wind and solar energy	start a wind farm project in timely reaction to spatial planning roll-outs
time lag	metal	groundwater contamination from mining only becomes apparent once the groundwater reaches the surface again	supply with critical metals, as by-products, is coupled to major metal demand, supply with critical metals might not meet demand and possibly lead to delays in supply	delayed perception of and reaction to (hidden) negative side-effects of mining
	RE	influences on species diversity when wind farms cause habitat changes	delays in construction because of the availability of materials or construction parts; delays because of long administrative processes	delayed perception of and reaction to e.g. spatial planning concerning the use of RE

temporal webs	metal	interplay of e.g. a volcano eruption and specific pressure and temperature that allow ore mineralization	interaction of supply and demand patterns (production and transportation times, raw material trade, ...)	connectedness of decisions and strategies/programs: issued to different points in time on different scales from global to local, time lags between decision taking and corresponding activities, differing durations of interlinked processes
	RE	interplay of weather conditions, e.g. intensities of wind and radiation, for RE generation	interaction of supply and demand patterns: daily, weekly, seasonal rhythms of demand <-> nonrelated rhythms of RE potential and supply	

4.2 STEP 2 applied: Temporal patterns of change in metal use and use of renewable energy technologies

We exemplify step 2 using the case of neodymium and thereby differentiate between the natural, socio-technical and regulatory spheres (Fig. 4). As described in section 3.2, we thereby differentiate four types of temporal patterns of change, depending on (i) the temporal extent of the change and (ii) its temporal irregularity. These are depicted in Fig. 4 below as a matrix with four quadrants. The matrix shows exemplary change patterns for each of the three spheres allocated to the respective type (i.e. quadrant); e.g., in the natural sphere (green circles), seasons are an example for rather short, rather regular change patterns (and hence allocated to quadrant 1), whereas habitat recovery takes considerably longer and is allocated to type 2. Processes of ore formation are both long and irregular (type 3). Reconnecting this to the general findings on temporal patterns (section 3.2), conclusions can be drawn on observability, predictability and (potentially) ability to control the processes mentioned here for the mineral-energy nexus: regular change patterns with short intervals (e.g. maintenance intervals for technical devices using neodymium (type 1), as well as for those with long intervals (e.g. nuclear half-life (type 2) are comparatively easier to predict. In contrast, it is more difficult to predict change with irregular patterns, again independent of whether they happen as an unforeseen single event (e.g. a mine waste spill, type 4), which might be followed by supply bottlenecks (type 4) or with a rather long time frame (e.g. the process of ore formation (type 3).

Implications for strategy design: Intervention points into a system may be considered promising when (i) it is easy to predict which change they will bring about on which time scale and whether and how it will affect others, (ii) change will occur within a relatively short period of time (if intended), so that effects can be observed and any necessary adjustments made in a timely manner; and/ or (iii) they are placed within a sphere that allows to exert influence on the system comparatively easy. For example, the growing use of renewable energy may increase pressure on neodymium availability. Since supply bottlenecks and price volatilities are rather difficult to predict, a joint strategy would have to consider these and could then also decrease price volatility.

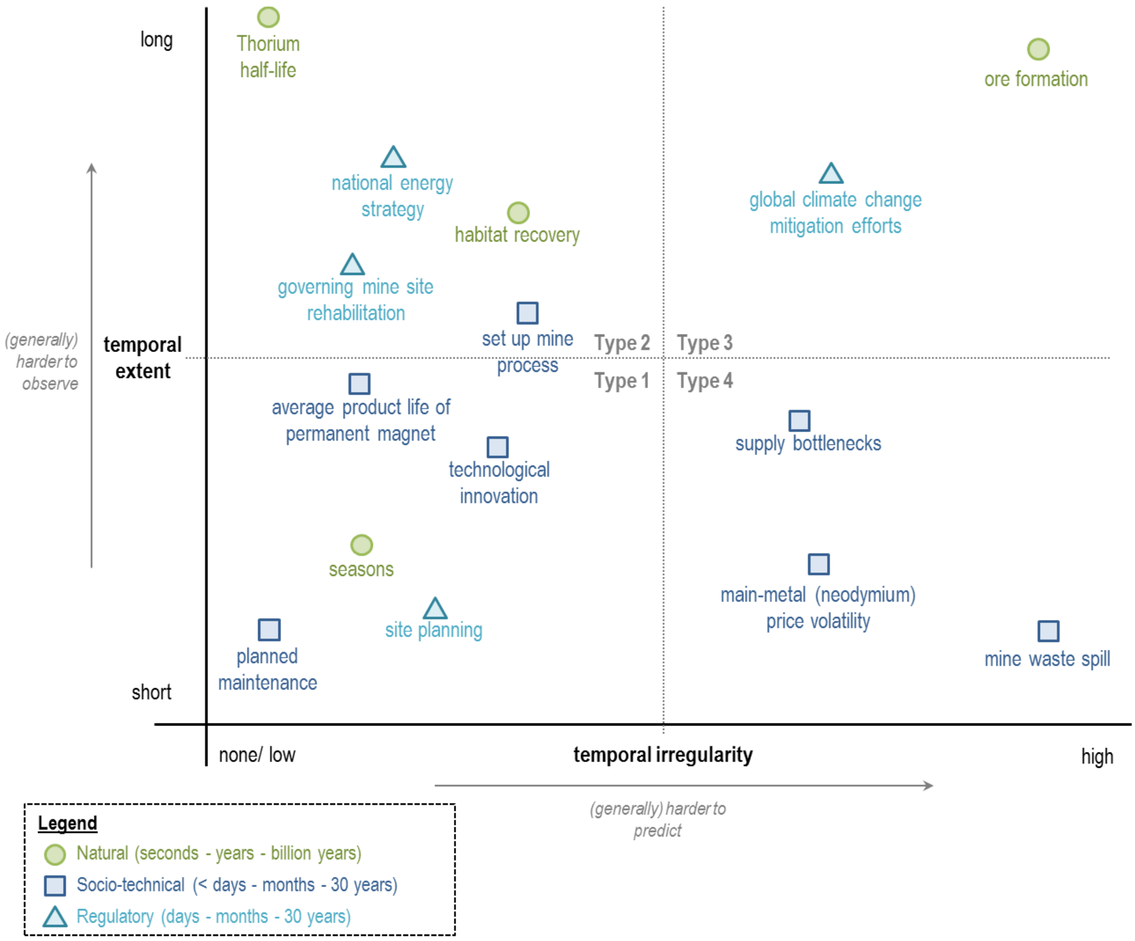

Fig. 4: Matrix of (relative) temporal irregularity of a system and (relative) temporal extent of system-inherent temporal patterns of change with examples evolving around the use of neodymium (own illustration)

One option to reduce resource shortages is the exploration and setting-up of new mine sites. Here, as shown by the following example, the involved processes can go beyond time horizons that can be properly overseen by humans (Pahl et al., 2014): The life cycle of a mine, which involves phases of exploration, mine-site development, the actual extraction of ore and finally its closure, usually covers a period of several decades (Environmental Protection Agency (EPA), 2012; University of Arizona, n.d.). While this prohibits a short-term reaction to supply shortages, the associated processes are still largely predictable. However, the actual operation phase is followed by various potentially very long-lasting processes. First, dealing with tailings and mine-site rehabilitation can be critical long-term issues, especially when radioactive by-products such as thorium are involved. Second, also unexpected and unintended events such as a spill of mining waste can considerably extend the temporal and spatial scale of (adverse) effects.

A second strategic option to address resource shortages is the development of more efficient recycling technologies or business schemes. The development of recycling approaches and their successful establishment in the socio-technical sphere may also take longer than the actual in-use phase of, for example, a wind turbine's magnet. Also, recyclability of products may be limited because materials are often mixed in very small concentrations (cf. e.g. Kümmerer, 2016; UNEP, 2013). Still, this second option would keep the impacts within a temporal range that can be better overseen by humans: Not only may the speed of innovation of recycling be increased through research funding; estimates based on average product life time (i.e. potential recycling material) are generally less afflicted with uncertainty than those on resource estimates (Speirs et al., 2015). Even though the two intervention options emerge from a similar context within the socio-technical sphere and cover comparable time horizons for their implementation, the associated effects of the two options differ strongly in their temporal extents. Therefore, the temporal implications strongly favor the recycling option over the mining option.

Weighing up intervention options and thus contributing to better anticipatory governance (Guston, 2014; Nordmann, 2014; Weiser et al., 2017) may also be a question of the sectors involved, since change patterns might be easier to predict in one sector than in another. A joint strategy for expanding renewable energy production would then need to allow for room to maneuver for volatilities of metal supply, but could already embrace the known natural patterns of climate conditions.

4.3 STEP 3 applied: Design interventions into metal use and use of renewable energy technologies in coherence with time ecology principles

Also considering the findings from applying step 1 and 2, the implications given in table 3 aim to contribute to coherent strategy making for renewable energy and metal use.

Table 3: Guidelines for designing interventions applied to the case of the mineral-energy nexus

Guideline	Implications for strategy design
Avoid temporal misfits	Temporal misfits may arise, for example, between the availability of necessary materials and the choice of preferred technology options as well as the money and knowledge needed, for both renewable energy products and recycling. As a consequence, a high demand for new energy technologies might not be met over the time span covered by an energy strategy due to a lack of available materials and experts. A change in market conditions would necessitate a switch in technologies to adapt to resource shortages. Another example are the unconnected temporal patterns of energy demand and fluctuating energy provision from renewable energy sources. Solutions such as storage and smart grids allow a closer temporal fit of these patterns, but necessitate again specific materials, knowledge and experts. Strategy building across sectors must thus consider potential misfits and bear enough flexibility for the system to adjust to these changing conditions. Strategy building should reflect this diversity of times and translate such understanding into suitable overall time horizons, concrete targets, and target years.
Minimize (negative) impacts	To minimize negative impacts, the strategy design should aim to reduce interferences in other spheres. For example, construction phases of wind turbines can be timed outside critical phases such as the breeding season. Such a thoughtful timing of an intervention reduces the impacts of felling trees, noise, and earthworks on the breeding animals. Similarly, the economic system may be more or less vulnerable to new regulations depending on the overall market situation, making it recommendable to time interventions accordingly.
Acknowledge or reduce delays	Designing a strategy at the mineral-energy nexus in awareness of wanted and unwanted possible delays, especially in large systems, emphasizes the role of precautionary approaches to be taken in situations inflicted by uncertainty. In other words, it might be wise not to wait until adverse effects have occurred, but to react to trends indicating unwanted dynamics as implied by (systemic) risk governance (Renn et al., 2011). Furthermore, as perception in general depends on position and experience, strategy building processes should incorporate a diversity of perspectives. It may thus be useful to introduce interdisciplinary practice-science advisory boards at the national level that are inspired by institutions such as the Intergovernmental Panel on Climate Change to accompany and guide the strategy development and implementation process over the complete time span of the strategy. Similar suggestions regarding a global governance system for sustainable resource management have been made by Bleischwitz and Bringezu (2008). Besides the International Panel for Sustainable Resource Management, which was established in 2007, this should include an international convention and an international agency for sustainable resource management.

5 Discussion

Our work illustrates that time is a relevant functional component of analysis in the context of transformations. Its integration must not stop at understanding systems, but pave its way towards developing sustainability strategies based on a deeper understanding of the role and diversity of time(s). While time ecology principles mainly contribute to system knowledge and partly neglect transformation knowledge (Brandt et al., 2013), many transformation concepts are found to lack an in-depth integration of time. Also, this perspective is not yet thoroughly discussed for the future of the mineral-energy nexus. Any observation or analysis, however, cannot be fully understood - let alone serve as a basis to govern system transformations towards sustainability - without having grasped the dynamics behind these systems, including their temporal patterns. Besides the actual time scales, this must also include system features such as recurring innovation cycles for new technologies. Considering time helps to operationalize comprehensive, joint analyses of two or more sectors and to cope with system-inherent times in a structured way, creating a greater awareness for dynamics across different sectors, i.e. at their nexus.

5.1 The "added value" of considering temporal diversity in sustainability transformation

Enhanced awareness for temporal diversity and potential path dependencies allows for a more detailed response to changes and interventions into the system. It demands a 'more process-oriented view' (Hofmeister and Kümmerer, 2009, p. 1382) that reflects the character of ongoing transformation processes and emphasizes that often unchangeable sequences (path dependencies) exist and must be considered when planning interventions into systems. This is closely connected to avoiding or minimizing (temporal) misfits, especially across several interconnected sectors and spheres. Misfits may be created between diverging time scales, but may also be an issue of timing, thus including other temporal features such as speed or point in time. Avoiding such misfits, or generally all patterns that might work adversely to sustainability, should be one central objective of all actions. Similarly, Munck af Rosenschöld et al. (2014) explicitly draw on the timescapes approach to address a lack of 'precision with regard to temporal complexity', emphasizing the importance of context as brought forward in the timescapes concept, in analogy to landscapes (Adam, 1998). To ensure coherence with the inherent time scales of a system, decisions should be taken in awareness of the longest relevant times of the respective system (Graßl, 1993), which implies the need for careful system observation.

Hofmeister and Kümmerer connect measures and levels of effectiveness to differing time scales in their temporal assessment of environmental impacts. A focus on impact also forces decision-makers to consider that the time scales of implementation processes may influence the (temporal and spatial) effectiveness of measures, since a system's sensitivity to changes may differ depending on phenomena such as elections or the seasons (Hofmeister and Kümmerer, 2009; Kümmerer and Hofmeister, 2008). The point of time in which a decision is taken, a technology enters the market, or a technical device is installed, highly matters, and may considerably influence other factors (including temporal ones) such as a product's life time. Additional factors include a technology's acceptance in society or whether its unintended adverse effects on the natural environment will be perceived and understood in time. Integrating temporal diversity into planning interventions, however, does not only refer to the question of "when" to intervene, but also to the "how". Acknowledging that systems are continuously changing and must do so to stay resilient (Gunderson and Holling, 2002; Held, 2001; Kümmerer, 1996), helps to consider system-inherent temporal patterns and, as a consequence, to design interventions into systems that maintain or enhance their resilience. There seems to be no one-fits-all approach to integrating and making use of temporal diversity. Still, such temporal considerations cannot replace but should complement other perspectives or approaches to system analysis or assessment in an integrative manner (Hofmeister and Kümmerer, 2009). For instance, we believe that the suggested time-in-transformations-approach has potential to expand and differentiate the temporal component of the leverage points concept (Abson et al., 2016; Meadows, 1999). For example, the guidelines (step 3) may support the design of interventions towards effective leveraging, as the consideration of diverse temporal dynamics can help to design interventions to suit the purpose for both shallow and deep leverage points.

Also, the relation to space and other contextual factors needs to be considered (cf. Kümmerer and Hofmeister, 2008), especially when time is not anymore reduced to quantification, but aims to include qualitative aspects ('making good use of time'). In that respect, we showed that reaction times differ across sectors. Complementing the spatial perspective, time can serve as a shared scale that offers an approach to accessing and making sense of the gap between urgency and long-term solutions and may thus also support transformation processes and according studies. The role of actors has not been in the focus of the work at hand. Nevertheless, it is not only important to consider who, based on their expertise and values, takes a decision. Also, the temporal implications of knowledge management and information flows between actors are relevant. An actor's individual context and position influences their perception of challenges and also the perception of their individual room to maneuver in relation to time. Perception is also discussed with respect to time: for time horizons extending 100 years, human perception is considerably limited, and rather the issue of imagination (Kümmerer, 1996; Pahl et al., 2014). This is an interesting factor for governing long-term sustainability challenges such as climate change. Considered to be a phenomenon that is 'long-term, delayed, with potentially rapid nonlinear changes' (Pahl et al., 2014, p. 385), climate change exemplifies a process that extends widely into the future and reveals long time lags between cause and effect. According to Pahl et al. (2014), people connect less to outcomes or rewards in the distant future, and time orientation and perception may differ significantly between individuals. Similarly, Giddens's paradox states that many people will do nothing concrete about global warming as long as it is not visible or tangible in their everyday lives. Paradoxically, waiting until climate change becomes concrete in the form of catastrophes will often mean that it is too late to act (Giddens, 2011). This means that special emphasis should be put on explicitly including this 'limitation' in our thinking and action.

Summing up, explicitly carving out the temporal dimensions of an intervention and its potential impacts may be of particular relevance in situations where complex interactions make it difficult to oversee all relevant cause-and-effect relationships, thus complementing, e.g., established approaches to system analysis or sustainability assessment. At this stage, our suggestions remain rather abstract or general in large parts. Follow-up steps and research should therefore include a concrete application to specific cases that allows for a recognition of the whole intervention process in detail and that pays tribute to the perception and time horizon of the involved actors. Above that, focus should be put on a closer temporal analysis of policy documents, strategies and transformation plans to provide a basis for improving and harmonizing policies through a times lense, and to further elaborate and test the temporal component of institutional fit.

5.2 New insights into the study of transformation processes in relation to time

Phase 1 – the pre-development or preparation - of a transformation process prepares the actual intervention and change process and thus demands system understanding across spheres and, for many sustainability challenges, across sectors (cf. e.g. Díaz et al., 2015; Future Earth, 2014). In both socio-technical systems (STS) and socio-ecological systems (SES), many preparatory processes happen in confined niches; but also processes on other levels and scales as well as cross-scale and cross-level processes are shown to be relevant (Göpel, 2016; Olsson et al., 2004). Step 1 of the time-in-transformations-approach contributes to this system understanding across levels, scales, sectors, and spheres because it plainly shows system-inherent time scales, potential path dependencies that may need to be overcome, and long-term risks that may need to be considered in a sustainability transformation. This temporal system understanding may help to decide what to do where. "Where", in this sense, means the sphere and sector, the scale and level of an intervention. Step 2 of the approach complements this, because it helps to reflect on our human capabilities to perceive and influence processes. This step can add to the understanding of possible temporal impacts of human activities in complex adaptive systems. Phase 2 of a transformation process, the actual intervention and change, is informed by third step of the approach. This step guides the design of interventions in a way that they acknowledge the temporal diversity and temporal elasticity of a system, and potential gaps related to the perception of processes. It therefore informs when and how to intervene in a system. Step 3 builds upon the system understanding developed in steps 1 and 2 and contributes to interventions in a way that a stabilization of the desired outcome can be achieved.

The time ecology concept allows for a more differentiated understanding of the temporal dynamics of a transformation process. While transformation research acknowledges that change processes happen at specific periods over time, time ecology considers a development's specific points in time, the rate of change and the specific time period when the process takes place. Transformational change as such is not explicitly considered in time ecology. The latter rather aims to incorporate (human) activities into (natural) systems in a way that the system-inherent temporal patterns stay intact and the system stays within its dynamic equilibrium and resilience (Kümmerer, 1996; Kümmerer et al., 2010). According to Gunderson and Holling (2002), it is necessary to overcome a system's resilience in order to enable transformation. Social-ecological systems naturally undergo constant evolution in a process of four linked and recurring phases: release, reorganization, exploitation, and conservation, which is described as panarchy. In this cycle, the speed and rate of change vary considerably. Change is most rapid in the "creative destruction" that marks the shift from conservation to release, while the system slowly evolves from exploitation to conservation (Gunderson and Holling, 2002). Further work might combine lessons from time ecology with the system understanding of panarchy and study how impacts of interventions differ when they are placed in the four phases of constant renewal and decline. For example, the effort to transform a system to a different state may be much higher when the system is in the stable exploitation and conservation phases compared to the release and reorganization phases. It might also be interesting to analyze whether the creative destruction or the reorganization phase of a system can be understood as a window of opportunity. Bearing in mind a system's adaptability and transformability, it may be necessary to intervene into a system at a time when it is more fragile and path-dependencies can be overcome easier in order to contribute to transformational change. Here, the time-in-transformations-approach offers to differentiate between the three spheres and may guide the design of interventions in such a way that the impacts mostly affect the sphere(s) that is or are supposed to change. Sustainability transformations usually aim to protect the natural sphere and alter technical and regulatory system elements. Thus, an intervention might ideally be placed when the natural sphere of a system is in a resilient state, but the socio-technical and the regulatory spheres are more fragile and allow change to occur.

6 Conclusions

Without considering time and temporal diversity, we would miss an opportunity to take better-informed decisions that can contribute to sustainability transformations. For governing complex and vital challenges such as transformations at the mineral-energy nexus, coherent strategies across sectors and levels, spatial and temporal scales are needed. In these strategies, time in all its facets can serve as a shared perspective on the system. The literature survey highlighted that the concepts of time ecology and sustainability transformations are connected and complement one another. This connection allows for a more comprehensive and differentiated system understanding that we operationalized in the time-in-transformations-approach. It builds on an in-depth understanding of temporal system characteristics and the dynamics across sectors, scales, and spheres. It also takes intended and unintended system dynamics, including temporal ones, into account and allows for an operational understanding of how to design and implement interventions. Even more important, it teaches us to take uncertainties as given, since our understanding of temporal dynamics remains limited.

Key findings from applying the approach to the case of the mineral-energy nexus exemplify the usefulness of the approach.

- *Eigenzeiten* and other temporal characteristics of the two sectors are very different. Still, the suggested approach allowed considering both sectors' dynamics together.
- The temporal perspective adds another layer to inform decision-making. For example, recycling is to be favored over mining from a temporal perspective, because of the extremely long and thus often uncontrollable time spans related to mining side-effects.

- A temporal perspective also adds another argument for the relevance of transdisciplinary practice-science collaborations to meet sustainability challenges. Because a higher diversity of backgrounds, experiences and trainings minimizes perception lags, transdisciplinary practice-science collaborations may contribute to avoiding problematic long-term developments. This is especially relevant for strategy building and risk governance for complex transformation challenges at the nexus of two or more sectors.

The suggested time-in-transformations-approach offers **two key contributions**:

- First, the approach allows making use of temporal system understanding for studying and fostering transformation processes towards sustainability. It may be included in or adapted to transformation management approaches such as transition management or adaptive management. In this context, the design guidelines for interventions of step 3 seem to be of particular interest.
- Second, the combination of time ecology with conceptualizations of transformation processes and the differentiation between spheres of a system allows placing and designing an intervention according to its intended effect. This may either be to protect a system and strengthen its adaptive capacity, or to add to its transformative capacity to destabilize and thus overcome unsustainable path dependencies. The approach allows placing interventions in a way that they trigger change in the targeted sphere, while negative impacts on the other spheres can be minimized.

The time-in-transformations-approach suggested in this article may help to avert decisions with potentially long-term adverse effects and enable to use opportunities. In doing so, it can also contribute to moving the ‘time rhetoric’ of the global sustainability discourse from an implicit, one-dimensional understanding to a shared and operational understanding of time and a more precise wording regarding temporal diversity.

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4.3 Understanding the modes of use and availability of metals - An expert-based scenario analysis for the case of indium

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Abstract

Natural resources are an essential pillar of today's economic and technological innovation. Growing demand, in particular for certain metals relevant for emerging technologies such as low-carbon energy production, has recently led to supply concerns especially in resource-importing high-tech countries in Europe and North America. Current approaches for facing the challenges linked to supply security and general modes of use and re-use often focus on either technological innovation or on the development of relevant governance interventions, but lack a common pursuance of objectives. We used an expert-based formative scenario analysis to examine the role these approaches play in the case of indium, and how they interrelate. We identified four exemplary scenarios that reflect how indium use may be influenced in different ways: (i) an extrapolation of today's trends (business as usual); (ii) a focus on the recycling phase; (iii) a governance system with stringent governmental regulations; and (iv) a governance system with well-balanced power structures and cooperation. We then analyzed these system scenarios in terms of their plausibility when assuming different surrounding conditions (shell scenarios) to determine their overall robustness. The evaluation of the scenarios showed that measures should be taken to optimize life cycle interfaces, including both primary and secondary production. We show that the state is a vital actor within the system of resource production and consumption, but has a limited operating range on an international scale. It must therefore provide the appropriate conditions to allow the evolution of private industry initiatives, which then can also contribute to the system's robustness. As a result, strategies targeting sustainable resource use could be the appropriate instrument to formulate a common objective and to more effectively coordinate such approaches for fostering sustainable indium use.

1 Introduction

Natural resources such as minerals and metals are an essential pillar of today's economic and technological innovation. Many geochemically scarce metals, which only occur in an average concentration in the Earth's crust below 0.01% (Skinner, 1979), fulfill crucial functions in emerging technologies including low-carbon energy production such as solar energy (Angerer et al., 2009). An increasing demand and changing world-market situations have put pressure on the availability of such resources. This has stimulated a discussion on their availability and potential "criticality" to sustain a large-scale implementation of these technologies (Angerer, 2010; EC, 2010; Schomerus et al., 2012; Wäger and Lang, 2010; Wäger et al., 2012), also calling for improvements in resource governance (Alley et al., 2008).

The term *criticality* must be distinguished from scarcity. While geo-chemical scarcity relates to the concentration in the Earth's crust (Skinner, 1979), scarcity - as used in scientific discussion - is a relative and dynamic concept relating availability and demand (Wäger and Classen, 2006). Beyond that, criticality involves a weighing up of multiple factors such as "geological, technological, economic, ecological and social issues" (Knoeri et al., 2013). Critical metals are therefore not necessarily scarce in a literal or geological sense. Several studies have recently evaluated the criticality of elements with different foci and from varying perspectives, such as time, scale and hierarchical level (Candelise et al., 2011; Erdmann et al., 2011; Graedel et al., 2012; UNEP, 2010). In that context, the US National Research Council (NRC, 2008) has developed a matrix to define criticality by the supply risk or risk of a supply restriction (horizontal axis) and the possible impact of such a restriction (vertical axis). Building on that, the European Commission (EC), in its attempt to formulate a comprehensive definition for criticality, focused on the aspects of a metal's economic importance and possible supply disruption risks as a means to distinguish critical raw materials from others (EC, 2010). Recently, Graedel et al. (2012) have introduced a third dimension to determine and quantify the criticality of a resource, extending the NRC matrix by a third aspect that highlights environmental issues.

This paper focuses on indium, a metal that has been rated critical in several studies (EC, 2010; NRC, 2008; Angerer et al., 2009; Erdmann and Graedel, 2011). Indium was identified in Germany in 1863 by Ferdinand Reich and Theodor Richter. It is transparent, "highly malleable and ductile" and owes its name to the "indigo color given off in its spectrum" (Chagnon, 2010), although the metal itself is actually silvery-white (Jorgenson and George, 2005). Its special characteristics make it suitable for application in various high-tech devices.

Several factors make indium a good case particularly for investigating the underlying dynamics that influence the supply and demand of critical metals for use in future technologies. One major factor is its vital role for the development of various future technologies, for which it is already used today. Currently, major areas of appliance include display technologies, thin film photovoltaic and white LEDs, others are semi-conductors and alloys (Angerer et al., 2009). Indium in the form of indium-tin-oxide (ITO) coatings is used in LCD and other flat screen devices, which currently makes up the major area of appliance (US Geological Service, 2013). CI(G)S (copper-indium-(gallium)-selenide/sulphide) absorber layers, an innovative thin-film solar cell technology, are ten times thinner than the conventionally used polycrystalline cells and can be evaporated directly onto the substrate, which makes the production of these devices more resource-efficient and less cost- intensive (Angerer et al., 2009; Fthenakis, 2009). These two areas of appliance are at the same time the most significant in terms of projections for future demand. In their report on raw materials for future technologies, Angerer et al. show that demand for indium will increase considerably over the next years. While ITO coatings would remain to be highly relevant for display technologies, the authors also expect a further increase in the appliance of CI(G)S solar panels, as steps towards their mass production would already be taken, offering potentials for cost reduction. They calculated an increase in annual indium demand from 234 tons in 2006 to 1911 tons in 2030. This would be three times the amount of the overall mine production in 2006, which was at around 580 tons (Angerer et al., 2009).

Another factor is the representativeness of indium for various critical metals related to the challenges associated with their making use of for appliance in emerging technologies throughout all life cycle phases. Amongst others, environmental harms and a high dependency on just a few existing producing countries – causing high price volatility – pose threats during the mining and refining stage. Equally important, matters of design and product development as well as modes of use and re-use have to be considered during later stages (Angerer et al., 2009).

Specifically, because its concentration in the Earth's crust is not high enough to make mining indium for its own sake economically viable (Chagnon, 2010), it is recovered as a co-product of other mining processes. Usually this is zinc mining, and small shares of tin (Jorgenson and George, 2005). It almost never occurs naturally in an elemental state (Angerer et al., 2009). In 2008, China had the highest access to indium reserves with a share of 75% (as well as the highest mine-production rate with a share of 45% in 2009), but estimations from known zinc reserves imply other considerable reserves to be present in countries such as Australia and Peru. Due to new calculations and estimations of deposits, specifications on indium reserves and the reserve base have varied strongly in the last years. The indium reserve base was calculated by the USGS to be approximately 2.800 t in 2006, and 11.000 t in 2007 (Angerer et al., 2009), with no further calculations published since then. Driven by the rather uncertain supply situation and high price- volatility, which make the supply chain very vulnerable, the search for appropriate substitutes for indium in certain applications has increased in the last few years. Some first achievements have been made that allow its substitution in both LCD flat screens and solar cells (Angerer et al., 2009; US Geological Service, 2014).

In order to cope with the above-mentioned challenges, scientists and practitioners have come up with a variety of ideas and approaches. Current approaches in practice as well as in research, however, seem to lack a common basis or objective, and mainly concentrate on just one of two focal points: (i) finding new and improving existing technological options along the life cycle of critical metals on the one hand (e.g. Buchert et al., 2007; Allwood et al., 2011), or (ii) ways to promote existing as well as new options through governance interventions on various hierarchical levels on the other (Bleischwitz and Bringezu, 2008; Wagner et al., 2007; Roßnagel and Sanden, 2007; Herrmann et al., 2012). In an attempt to combine these two approaches, Wäger et al. (2012) have developed a generic framework to structure possible fields of intervention for scarce metals that is still to be applied to and tested for single scarce metals. Therefore, this paper will relate to the latter for the case of indium.

Here we apply an expert-based formative scenario analysis (FSA) to identify requirements for robust sets of approaches of technology options and corresponding governance interventions that could support a long-term availability of indium, which is considered to be one important aspect when targeting sustainable resource use. Specifically, we collect, structure and analyze current approaches for dealing with (the threat of) indium criticality in order to investigate their impact on other approaches. We synthesize the information in coherent sets, analyzing their interrelations to identify vital factors within the latter. Finally, we conduct a robustness appraisal to understand possible interactions with factors outside the observed system, identifying those characteristics that would make a certain set of approaches robust even under varying external conditions.

Thus, the purpose is to develop a profound understanding of the system rather than actually defining or evaluating what could be deemed “a sustainable use” of critical metals. This would have meant to include a broad variety of further factors including environmental and social criteria related to mining or modes of consumption. Our analysis is not intended to engage with supply and demand projections, which often focus on primary production rates only and thereby neglect technological progress in e.g. recycling or substitution as well as other factors associated with the criticality of a resource. Rather, it is assumed in the scenarios that indium could reach criticality due to an increase in demand and that this is an outcome which one may wish to avoid. The study includes existing theories and research from various disciplines and integrates them with the ideas and assessments of experts from science and practice. In doing so, it takes on a very comprehensive perspective, offering some valuable implications related to possible measures tackling the identified challenges in a solution-oriented manner not only for technological developments, but also for the regulative frame in which they evolve in much greater detail than previously applied.

2 Methods

The research design consisted of three major phases: (i) a collection of current approaches of technology options and governance interventions based on literature and expert interviews, (ii) a formative scenario analysis, and (iii) a robustness appraisal of selected scenarios (compare Fig. 1). Research focused on interventions from the perspective of Germany, that is, an EU-member and an indium-importing country with a high resource demand for technological appliances. By developing scenarios for the year 2030, we considered mid-term developments throughout a time frame of 15-20 years. Nine experts were involved at two stages of the process in order to gain a comprehensive overview on the subject. They were selected to represent the private industry and single interest groups (such as nature conservation unions or other NGOs) as well as science and research institutions. In addition, they covered expertise related to all phases of the indium life cycle (Fig. 2).

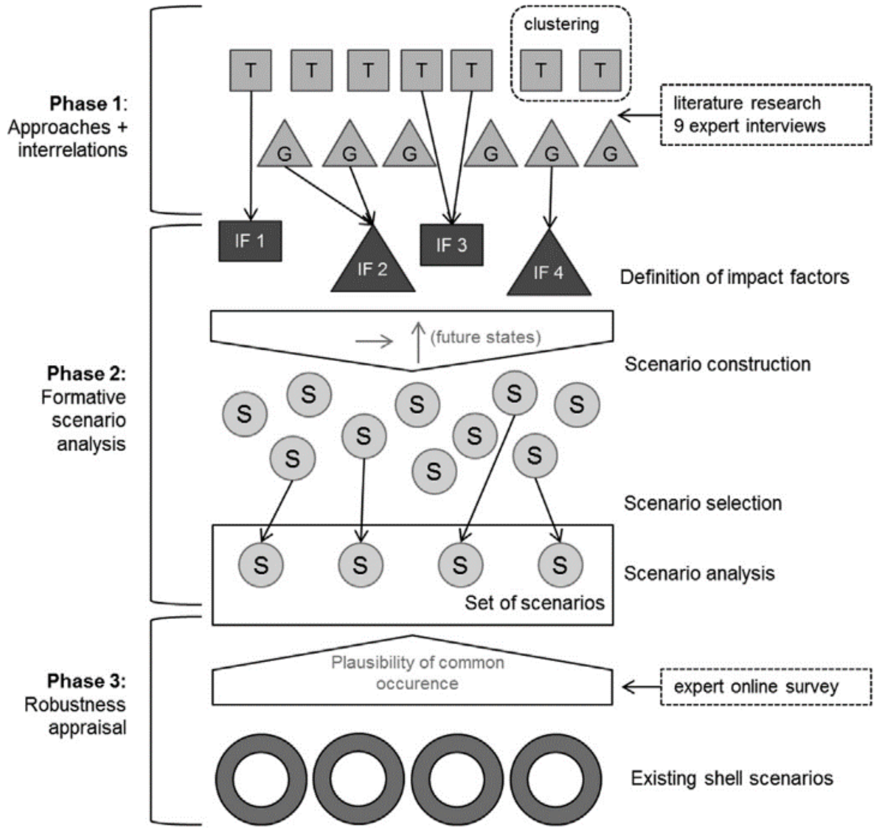

Fig. 1. Methodical approach (T = technology options, G = governance interventions, IF = impact factor, S = scenario; the two phases of expert involvement are shown in dotted rectangles).

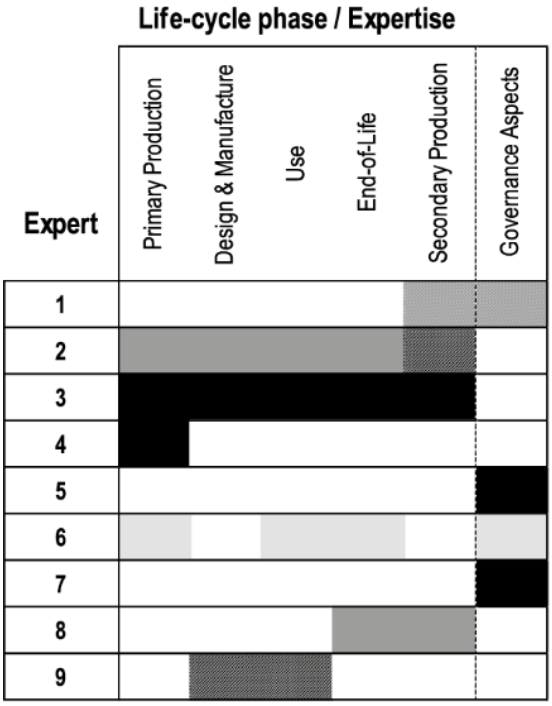

Fig. 2. Expertise for life cycle phases and thematic aspects within the expert group (black markings showing a science-related expertise and dark gray markings showing an industry-related and light-gray markings showing a stakeholder or civil society related expertise (hatchings for ambivalent roles); source: own illustration).

2.1 Phase 1: approaches & interrelations

To gain an overview of the system under investigation, we first consulted the literature on metals and resource use, as well as studies on recent developments in technological innovation and resource governance. We then conducted interviews with each of the experts to verify and round up the information collected through literature review. As a consequence, we first identified, structured and clustered technology options based on the challenges we found, and grouped the governance interventions in accordance with existing clusters made by Kloepfer (2004) and Sanden et al. (2011). Second, we structured the various approaches (governance interventions as well as technology options) along the metal life cycle, distinguishing the following phases based on Van Berkel (2007) and Hagelüken and Meskers (2010): (i) primary production, (ii) design and manufacture, (iii) use, (iv) EoL (end-of-life) treatment, and (v) secondary production (a similar structure was chosen by Wäger et al. (2012) for their review of intervention options). As a consequence of that first phase we achieved a comprehensive collection of approaches fostering a sustainable indium use and governance interventions that might help to promote the implementation of the latter.

2.2 Phase 2: formative scenario analysis (FSA)

Based on the information gathered in phase 1, we then applied the principles of a formative scenario analysis (FSA) (following Scholz and Tietje, 2002; Spoerri et al., 2009) in order to define and evaluate possible sets of the collected approaches.

2.2.1 General principles

In an FSA, parameters of a given system – called *impact factors* – are defined that have a distinct influence on other parameters or are highly influenced by others. A set of these impact factors (IF) forms the basis for the scenario analysis. The direct influence these impact factors have on each other is then assessed in an impact matrix (see App. A), that gives insights into each factor's systemic relevance in the observed system as well as into its overall system dynamics. Following the thorough analysis of the system, possible future states for each impact factor are defined. By combining all future states of every impact factor with all others, all possible scenarios are constructed. This shows that a scenario is at its core a "combination of levels of all impact variables" (Scholz and Tietje, 2002). To omit the scenarios that are logically not coherent (inconsistent), a consistency matrix is used that contrasts the consistency of each impact factor's future state with all future states of the others.

Finally, a small set of scenarios is selected from the pool of all possible and consistent scenarios. The selection is based on defined selection criteria in order to achieve a set of scenarios that is both small enough to manage and sufficiently diverse. The selected scenarios shall vary in vital parameters to allow their interpretation regarding the objectives of the analysis (Spoerri et al., 2009)

2.2.2 Application for this study

In this study, a selection of the technology options and governance interventions identified in phase 1 constituted the set of impact factors. In assessing their impact on each other in an impact matrix, we classified the impact factors as either.

- active (i.e. highly influential on others),
- passive (i.e. highly influenced by others),
- buffering (i.e. neither very active nor passive, indicating a minor possible importance for the system dynamics) or
- ambivalent (i.e. with high activity as well as passivity ratings, indicating a critical role of the factors for the system dynamics).

These are illustrated in a system grid that locates each impact factor relating to its activity and passivity values. For the system analysis we used the SystemQ software (Tietje, 2012b). Additionally, here we compared the systemic relevance with an expert assessment of the technology options' future relevance. On this basis we selected a set of impact factors for the further analyses (IF_1 to IF_n).

We defined possible future states for each of the selected impact factors: One (e.g. IF_{1a}) represented today's state and the other (e.g. IF_{1b}) depicted future prospects of today's trends for the year 2030 that reflected the information given by the experts or found in literature. These were then combined to scenarios (i.e. consistent sets of future states). We selected the scenarios using two complementary approaches: a data-driven, bottom-up and a concept- driven, top-down approach. The first selection criterion was logical consistency: The consistency (or plausibility of a common occurrence) of each future state with the future state of any other impact factor was evaluated in a consistency matrix using a four-step scale:

-1 = inconsistency (meaning e.g. IF_{1a} inconsistent with/hindering IF_{2b})

0 = possibility (meaning IF_{1a} and IF_{2b} co-exist and do not influence each other)

1 = support (meaning IF_{1a} and IF_{2b} may co-exist and even support each other)

2 = pre-requisite (meaning IF_{1a} being a pre-requisite for IF_{2b})

Adding up all consistency values for a certain scenario yielded its overall consistency (additive consistency) (Tietje, 2005). Scenarios with inconsistencies were excluded from the selection to ensure that none of the selected scenarios contained future levels that would actually contradict or exclude each other. We then applied a data-driven (bottom-up) approach to select a set of scenarios, which represented a broad range of possible developments, but was at the same time sufficiently differentiated. This was done by applying the max-min-selection approach developed by Tietje (2005), using the SystemKD software (Tietje 2012a). While this approach ensured that the process of narrowing-down the set of selected scenarios was based on objective criteria, the following, complementing concept-driven (top-down) approach allowed for the inclusion of "conceptual ideas about the future of the case" (Scholz and Tietje, 2002) that had arisen from the previous steps of the analysis (i.e. literature review and expert interviews). Here, we focused especially on such scenarios that would allow a deeper insight into the role of certain technologies as well as promising combinations of governance interventions, thereby attempting to identify vital parameters to influence the system.

2.3 Phase 3: robustness appraisal

In a final step, we conducted a "robustness appraisal" based on the robustness assessment described by Wöhrnschimmel et al. (2002), which assesses the plausibility of certain system scenarios under varying surrounding conditions. The experts were asked to rate the consistency of the four selected system scenarios with already established surrounding conditions *(shell scenarios)* from the Global Scenario Group (Tellus Institute, 2009; Raskin et al., 2010) (see Fig. 3). We then compared this formative appraisal to the results of complementing intuitive judgments by the research team.

A. **Market Forces – Market-centered development:** "Market Forces is constructed as a future in which free market optimism remains dominant and proves well-founded. As population expands by 40 percent by 2050 and free trade and deregulation drive growth, the global economy expands over three-fold by 2050, eightfold by 2100." (Raskin et al. 2010)
B. **Policy Reform – Directing Growth:** "The Policy Reform scenario explores the requirements for simultaneously achieving social and environmental sustainability goals under high economic growth conditions similar to those of Market Forces." (Tellus Institute 2009)
C. **Fortress World – An Authoritarian Path:** "The Fortress World scenario (…) features an authoritarian response to the threat of breakdown. Ensconced in protected enclaves, elites safeguard their privilege by controlling an impoverished majority and managing critical natural resources, while outside the fortress there is repression, environmental destruction and misery." (Tellus Institute 2009)
D. **Great Transition – A Sustainable Civilization:** "The Great Transition scenario (…) depicts a transition to a society that preserves natural systems, provides high levels of welfare through material sufficiency and equitable distribution, and enjoys a strong sense of local solidarity." (Tellus Institute 2009)

Fig. 3. Short descriptions of shell scenarios (with descriptions taken from the original Global Scenario Group texts).

3 Results

3.1 Approaches & interrelations

The literature review and interviews revealed five major challenges that ought to be addressed to approach indium criticality and contribute to its sustainable use: (i) its relative (i.e. not absolute) scarcity and general finiteness, (ii) insecurities concerning (primary) indium stocks, (iii) a lack of coordination throughout the various life cycle phases, (iv) high losses and dissipation throughout the whole life cycle due to, among others, a lack of appropriate (production) processes, and (v) environmental damages.

We could identify 16 technology options and 41 governance interventions to address these challenges (see App. B and C). To correspond with the challenges described above, the technology options were clustered as follows: (i) substitution (i.e. the use of different materials that fulfill the same function), (ii) increased access to stocks (e.g. improved exploration and primary production efficiency), (iii) interface optimization (i.e. closing the material-cycle), (iv) efficiency improvements (e.g. material or production process efficiency and minimization of losses) and (v) conservation (i.e. the reduction of environmental impacts and non-metal resource use such as water) (see App. D).

The governance interventions were clustered according to their character of regulation, institutional level and binding force, as follows: (i) support programs and strategies, (ii) private economy measures & voluntary commitment, (iii) standard setting, (iv) governmental intervention, legal acts & guidelines, and (v) international institutions and agreements (see App. D).

Where applicable, we assigned the different technology options and a selection of the governance interventions mentioned most frequently by the experts and in literature to the indium life cycle phases (Fig. 4).

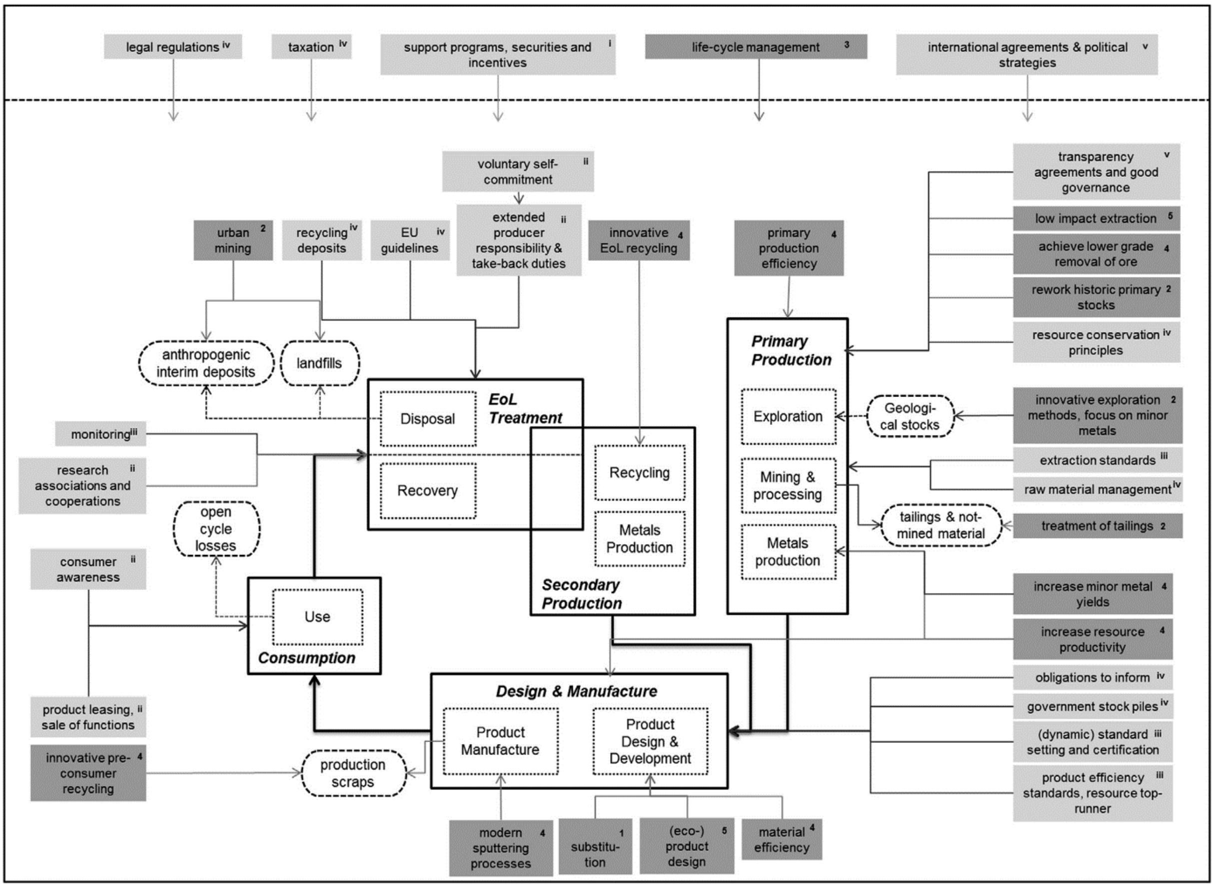

Fig. 4. Indium life-cycle phases with assigned technology options and governance interventions (own illustration, life-cycle according to Van Berkel 2007; Hagelüken and Meskers, 2010). (The center of the figure shows the main phases of the indium life-cycle from the exploration of geological stocks to its disposal or recycling; the various technology options (dark gray rectangles) and governance interventions (light gray rectangles) are settled around the life-cycle phases; each of them is labeled with a small number, which depicts the according cluster to which they belong (compare Section 3.1: 1 = substitution, 2 = increased stocks, 3 = interface optimization, 4 = efficiency improvements, 5 = conservation measures; i = support programs and strategies, ii = private economy measures and voluntary commitment, iii = standard-setting, iv = governmental intervention, legal acts and guidelines, v = international institutions and agreements. The governance interventions and technology options above the dotted line cannot be assigned to a single life-cycle phase, but affect various phases).)

3.2 Formative scenario analysis

Based on the approaches identified in phase 1 we formulated a final set of 16 impact variables (six technology options and ten governance interventions) (Table 1).

Resulting from the impact matrix (compare App. A), the *system grid* (Fig. 5) gives a first insight into the systemic relevance of the impact variables, classifying them as either active, passive, buffering or ambivalent.

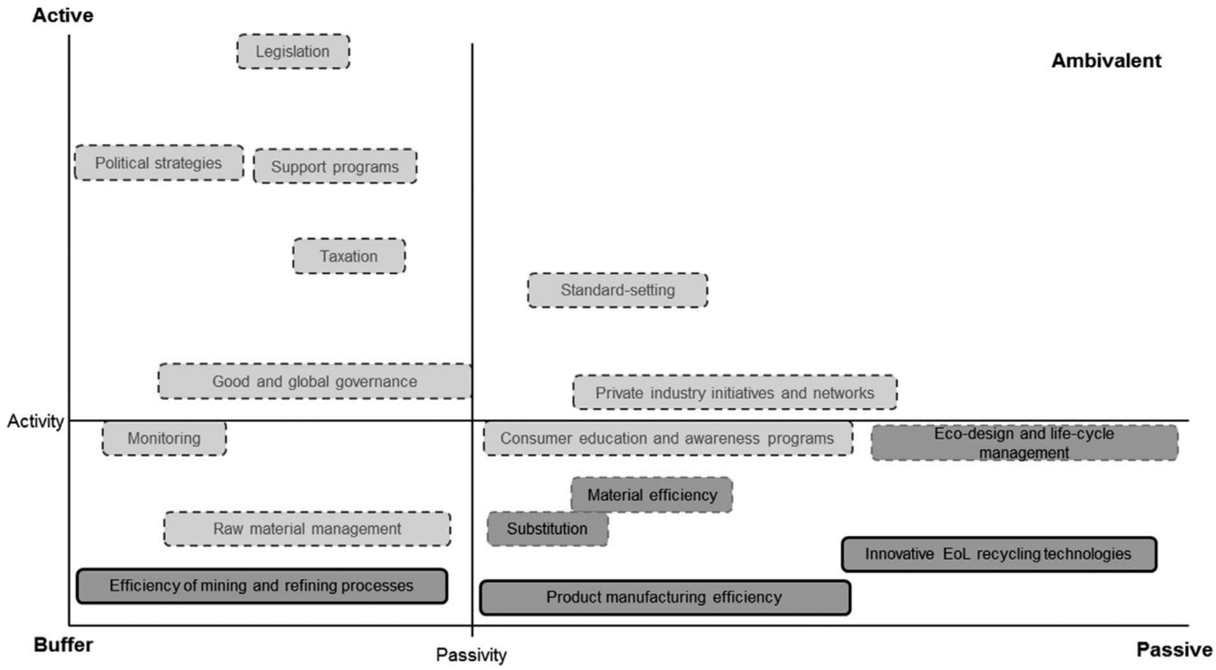

Fig. 5. Systemic relevance of the impact variables (governance interventions are marked in light gray, technology options in dark gray; impact variables are characterized as either active, passive, ambivalent or buffering based on the impact matrix; the three technology options with a high future relevance as assessed by the experts are marked with a dark frame; compare Table 1 for more detailed descriptions of the impact factors (SystemQ software, Tietje, 2012b)).

We found the *systemic relevance* of governance interventions ranking generally higher than the technology options. We contrasted these results with the perceived future importance and contribution to sustainable development as ranked by the experts (perceived future relevance). This was considered vital for a comprehensive understanding of the system, especially with a focus on the factors' importance for technological innovation. Referring to the systemic relevance, eco-design, material efficiency and substitution technologies were seen to be the most relevant and influential technology options within the system. The perceived future relevance, by contrast, implied a prevalent importance of innovative recycling methods, improvements in primary production and product manufacturing efficiency, indicating that a special focus should also be put on promoting these technologies.

Table 1. Final set of impact variables and their descriptions (1-6 = technology options; 7-16 = governance interventions).

Impact factor		Description
1	Primary production efficiency	Methods, processes and technologies targeting minimizing losses as well as energy & resource consumption during exploration and primary production (mining and refining)
2	Product manufacturing efficiency & pre-consumer recycling	Methods, processes and technologies targeting minimizing losses during product manufacture and recovering production scraps (pre-consumer recycling)
3	Material efficiency	Methods, processes and technologies targeting reducing the (indium) material input per unit while keeping up its functionality
4	Eco-design and life-cycle management	Methods, processes and technologies targeting facilitating recovery and re-use of materials throughout the whole life-cycle, including design for urban mining
5	Substitution	Methods, processes and technologies targeting finding materials to substitute indium in products while keeping up their functionality
6	Innovative EoL recycling technologies	Methods, processes and technologies targeting an innovation of recycling and treatment of EoL products in order to increase secondary production stocks, including urban mining technologies
7	Support programs	Instruments of financial and structural support to encourage research and investment, nationally and internationally, and by the state or state-affiliated organizations targeting new technologies, exploration methods, etc.
8	Legislation	Instruments using legal/binding force to influence resource use and disposal on different levels, through legal acts on state level or directives to be implemented by the states at supranational level (such as the EU)
9	Taxation	Instruments aiming at influencing resource use through financial incentives or hurdles, posed by the national state
10	Monitoring and other data sampling	Instruments used to enhance knowledge on indium stocks and flows towards optimizing and organizing the indium life-cycle, nationally and internationally, and realized by the state and its organizations, or an international cooperation of these
11	Political strategies	Instruments defining objectives and desired developments for a certain area or sector, nationally or internationally, and by the state or supranational organizations (might target private industry, consumers or any other possible stakeholder)
12	Private industry initiatives and networks	Instruments targeting increases in resource efficiency, recycling rates or a minimization of metal losses throughout the whole life-cycle, nationally and internationally, initiated by the private industry through voluntary commitment or company networking
13	Standard-setting incl. resource top-runner	Instruments that aim to influence resource use through certification, the definition of standards or other quality criteria, or resource top-runner approaches on a national or international level
14	Consumer education and awareness programs	Instruments aiming at raising awareness for resource efficiency, recycling, etc. (can be national as well as international, and initiated by the state as well as different organizations or interest groups)
15	International institutionalization	Instruments aiming at the creation of a global resource governance regime, i.e. a co-operation of various national states and organizations of any kind on an international level
16	Good governance and transparency initiatives	Instruments employed to enhance transparency and sustainability of resource production and trade, be it national campaigns or international initiatives, and organized by private as well as state-affiliated organizations

The final set of 16 impact factors with two future states each (see App. E for a description of the future levels), resulted in a total of 65,236 possible scenarios, from which four scenarios were selected: One extrapolating today's trends (business as usual) (1), one depicting a "recycling society" (2), one representing the situation in which a state regulates indium use rather stringently (3) and one with balanced power approaches for governing indium use (4). Table 2 shows some relevant characteristics of the selected scenarios, scenario highlighting that all of them are sufficiently consistent and different from all others, representing a diverse spectrum of possible future developments. A short storyline for each scenario is given in Fig. 6 (see App. F for full descriptions of each).

Table 2. Basic information and future states of the four selected scenarios (1 = today's state; 2 = desired future state as derived fromliterature and interviews; characterizing factors are put in bold letters).

	Bottom-up	Top-down	Add. Consistency	Inconsistency	Distance to scenario				Primary production efficiency	Product manufacturing efficiency and pre-	Material efficiency	Eco-design and life-cyclemanagement	Substitution	Innovative EoL recycling	Support programs	Legislation	Taxation	Monitoring	Political strategies	Private industry initiatives and networks	Standard setting	Consumer education and awareness programs	International institutionalization & global governance	Good governance and trasparency initiatives
					1	2	3	4																
1 Trend extrapolation		x	42	0	3	-	7	3	1	2	2	2	1	1	2	1	1	1	2	2	2	2	2	2
2 A recyclingsociety	x	x	40	0	-	3	6	4	1	2	2	2	1	2	1	1	1	2	2	2	2	2	2	1
3 Stringent regulation	x	x	40	0	6	7	-	4	2	2	2	2	1	2	2	2	2	2	2	1	1	2	1	1
4 A world of cooperatio	x	x	62	0	4	3	4	-	2	2	2	2	1	2	2	2	1	1	2	2	2	1	2	2

1. **Trend Extrapolation:** Improvements have been achieved especially in material efficiency, but there is still only limited indium supply security to meet the increased demand due to a lack of technologies and regulations aiming at enhancing primary as well as secondary indium supply.
2. **A Recycling Society:** Society is highly aware of the necessity of conscious resource use, with the state building on an optimization of in-use material flows and secondary production through implementation of soft instruments & development of industry networks, but is not further promoting primary metal supply, resulting in on-going supply insecurities with regards to the increased demand.
3. **Stringent Regulation:** The state directs indium use in a variety of sectors and life-cycle phases. Further, it supports research and resource exploration efforts, leading to a generally high primary and secondary indium supply, but with high financial costs and without supporting private economy engagement.
4. **A World of Cooperation:** A strong emphasis on the alignment of state and private industry activities, plus intense collaboration with international partners, allows a far-reaching reduction of tension on the international resource market and a closing of life-cycles for indium-containing products, thereby addressing major criteria for criticality and achieving a rather stable supply situation even for a steep increase in demand.

Fig. 6. Short descriptions of the four selected scenarios.

The analysis of the four scenarios gives insight from two different perspectives: (i) it shows which governance interventions would be most relevant to support different variations of technology options; (ii) it represents different possible developments of the technological state-of-the-art when assuming different patterns of governance interventions.

An extrapolation of today's trends as depicted in scenario 1 would not notably contribute to a reduction of indium criticality. With no considerable improvements in the secured provision of primary metal, interface optimization or efficient recycling technologies to keep indium within the system, the supply situation would not change substantially compared to today, which might increase tension when indium demand rises. Scenarios 2 (Recycling society) and 3 (Stringent regulation) reveal two different ways to cope with a situation as described in scenario 1: In scenario 2, emphasis is put on an optimization of specific life cycle phases and improved recycling structures, while at the same time primary production-rates remain low. The focus of action is set on creating awareness and developing company networks, as well as other means of cooperation, and directing behavior through non-state driven measures. In contrast to this, in scenario 3 the state has a more active role and applies considerably stricter and more top-down instruments for directing indium production and use, achieving advancements not only in recycling, but also in primary production.

The characteristics of scenarios 2 and 3 are brought together in the last scenario 4 (Cooperation), where the state has applied several measures, such as an accorded legislation, to direct indium use. However, it also leaves space for parallel voluntary and bottom-up measures to evolve. Such ideas of a sharing of tasks between state and non-state actors were brought up by various experts during the analysis and were thus a common feature throughout the analysis and the evaluation of possible measures. An example for an instrument that is built up on such forms of cooperation would be standard setting. These were also considered vital for the promotion of certain technologies and life cycle phases: for improvements in terms of eco-design and lifecycle management and for the development of innovative recycling technologies, the experts considered private industry initiatives and networks very suitable. This would make such forms of cooperation essential components for reaching a more sustainable indium use regarding the EoL and secondary production phase, but also in terms of optimizing the indium flows throughout all phases. Additionally, they offer a comparably high degree of participation and room for action for a variety of stakeholders, avoiding the danger of the concerned actors feeling "steamrolled" by the state. Instead, it allows the private industry to act within that frame and complement measures in their own interest and with their very own competencies.

3.3 Robustness appraisal

Table 3 shows the results of the robustness appraisal by the experts and the research team. Both, the experts as well as the research team, assessed scenario 4 (World of Cooperation) as the most robust, as they both considered it to be plausible under all but one of the assumed surrounding conditions. Scenario 3 (Stringent regulation) was considered plausible under Policy Reform conditions by both groups, as well as under all others surrounding conditions by just one of the two groups. This makes scenario 3 the second-most robust scenario. Both scenarios 1 and 2 were assumed to be plausible for the shell scenarios “Policy Reform” and “Great Transition” only. From a different perspective, these two shell scenarios were also assumed to allow all or most of the system scenarios to evolve.

Table 3. Overview of the robustness appraisal results (R + E = expert and research team assessment, R = research team only, E = expert assessment only, - = neither experts nor research team considered a common appearance plausible).

Scenario	Market forces	Policy reform	Fortress world	Great transition
1: Trend extrapolation	-	R	-	E
2: Recycling society	-	R	-	R + E
3: Stringent regulation	R	R + E	R	E
4: A world of cooperation	R + E	R + E	-	R + E

4 Discussion: implications for indium modes of use and availability as a contribution to a more sustainable indium use

The results provide some implications concerning the role of the single approaches within the system as well as concerning vital requirements when targeting a more sustainable indium use.

4.1 The role of single approaches

The extensive collection of approaches towards a reduction of indium criticality offers a new perspective on how to understand, structure and improve their interrelations. It must be noted, though, that a high impact within the analyzed system does not necessarily imply a high “contribution” of approaches to sustain able resource use. For example, innovative EoL recycling technologies and product manufacturing efficiency, which had rather low activity/passivity scores, were considered by the experts as highly important for a contribution towards a sustainable use of indium (compare Fig. 5). In fact, the latter are also considered as vital on the road to an increased decoupling of growth and resource demand in the German Resource Efficiency Program (ProgRess) (BMU, 2012). This shows that approaches or instruments may contribute substantially to fostering sustainability, even when they do not interact with other components of the system. In contrast to that, eco design and lifecycle management, as well as material efficiency, were considered comparatively influential within the system, but ranked rather low in terms of future relevance. This shows that they are vital and influential factors that determine, for example, a later recyclability. However, the recycling technologies themselves are considered to be more important. A methodological reason why the governance interventions are generally ranked more active than the technology options in this study is the fact that the interventions aim at influencing or supporting the technology options, while the target variables of the technology options (e.g. recycling rate or environmental impact) are not part of the system analysis.

Concerning the impact of governance interventions, factors with the highest impact scores were legislation, support programs and political strategies with a particularly high activity, and private industry initiatives and standard-setting with a high passivity. The high impact of political strategies is probably reflected in the wish for a common basis and structure behind the actions taken by the state. This was quite often brought up by the experts, especially in terms of (financial) support, but also in setting appropriate boundary conditions for private industry actions. The high impact score of legislative measures can be explained in two ways: either by the fact that legislation generally serves as the basis for all kinds of regulation of resource-related issues, from resource-efficiency standards in primary production to regulations concerning their disposal and recycling; or methodically as a result of the rather broad definition of the impact factor.

Table 4. Comparison of intervention options for Wäger et al. (2012) and for the approach at hand.

Intervention options for scarce metals according to Wäger et al. (2012)	Approaches for indium as collected for this study
Institutional setting + knowledge provision	Legislation Support programs Political strategies Taxation Monitoring
Good governance and transparency	Good and global governance
Certification/labelling Sustainability standards	Standard-setting
Leasing/selling functions	Private industry initiatives and networks
Sufficiency	Consumer education and awareness programs
Product lifetime Product design Recycling chain interfaces	Eco-design and life cycle management
Materials efficiency	Material efficiency

Substitution Recycling of manufacturing scrap	Substitution Product manufacturing efficiency
(Eco-) efficient EoL product collection and re-covery systems	Innovative EoL recycling technologies
Eco-efficient mining/refining processes Recovery of historic materials	Efficiency of mining and refining processes
Stock-piling	Raw material management

Equally, experts had considered the generally long time periods of developing and applying new technologies, as well as the cost- intensiveness of innovation processes to be the biggest constraints for the broad implementation or large-scale improvement in terms of technological innovation. These could be targeted by measures taken to financially or structurally support research and development processes, showing their vital importance when speaking of the interactions of technology options and governance interventions.

The review of possible interventions for a sustainable use of scarce metals by Wäger et al. (2012) brought up a similar collection of approaches as identified here. This generally confirms the applicability of that generic framework on single critical metals. However, both studies have a slightly different structure and focus: While most interventions identified by Wäger et al. were also found to be relevant for indium, our study put a stronger focus on a differentiation of technological or governance-related approaches and their interrelations (compare Table 4). Consequently, our set of approaches shows a more detailed differentiation of what Wäger et al. sum up as “institutional setting” and “knowledge provision” and therefore allows for more distinct propositions on the interrelations of the two “types” of approaches.

4.2 Vital requirements for a more sustainable indium use

Building on the scenario analysis results, the discussion on requirements for building robust sets of approaches towards a more sustainable indium use evolves mainly around (i) the role assigned to the state or other governing bodies and the private industry or free market dynamics respectively, and (ii) strategies as a possible means to define common objectives across national borders, actors and disciplines.

4.2.1 Role of state and private industry

Mainly two aspects make the "Stringent regulation" and "Cooperation" scenarios robust within the four analyzed shell scenarios: Firstly, they correspond well with the manner of organization and regulation of the Policy Reform and Great Transition shell scenarios because they are also characterized by a sense of balancing measures, including state initiatives. Secondly, such systems have the capacity of adapting rather quickly to changes of major influential factors (such as a volatile indium price and a competitive market). In both cases, the state can set an appropriate frame for regulations in reaction to these altering conditions. By comparison, constellations with less strict or less strategic mechanisms on an overarching level (such as a focus on the self- regulation of the market or an education and awareness-focused society) cannot adapt accordingly within the necessary time frame. A necessary pre-condition, though, which is applicable especially for the "Cooperation" scenario, would be flexibility of the legislative system, allowing for fine adjustments to be made rather quickly. One possibility practiced in Germany that might also be an option for the state in the "Stringent regulation" scenario would be the formulation of administrative regulations such as technical instructions (Technische Anleitungen, TA). Directed at the administrative bodies, this form of delegated legislation accompanies and concretizes the more general legal acts, upon which they are based, but can be adjusted to state-of-the-art knowledge and bench marks considerably faster than the legal act itself (Maurer, 2011).

As long as such legislation does not yet exist for the regulation of critical metal use, (political) decision-makers may take the following steps: (i) prioritizing actions on the basis of the current state of research (regarding technological progress, resource availability and life cycle analyses), (ii) promoting international agreements especially for those metals that exist in just a few countries, but are not being recycled on a broad scale yet, to minimize the potential for geopolitical tension, and (iii) promoting national to EU-wide agreements that are as specific as possible, matching the according metal, and letting economic and other stakeholders participate in the decision-making process.

Industry members, on the other hand, should try and fill the remaining regulative blanks by cooperating with other companies to find marketable solutions quickly, especially for closing life cycles and viable recycling technologies. This might become especially relevant for actions taken on a local to regional scale. Examples include the implementation of cooperative networks as well as the development of new business models.

The importance of building such co-operations was emphasized by several experts especially for the case of recycling of indium and other critical metals, due to their generally small concentration in products that makes recycling often improvident for one company alone. Networks may be initiated within a certain region or branch and with various scales and purposes. Eco-industrial parks (EIP) can be seen as co-operations on a small scale and would be particularly interesting concerning the ex- change and re-use of by-products of industrial processes (Gibbs and Deutz, 2007; Lowe, 1997). Examples include Kalundborg in Denmark (Lowe, 1997) and the Ulsan Eco-Industrial Park in South Korea (Behera et al., 2012). To date, however, there have been no accounts of EIPs focusing on such inter-firm recycling concepts especially for critical metals.

On a larger scale, existing networks in Germany include those of producers and recyclers of PV-devices, which e according to the EU directive on Waste Electrical and Electronic Equipment (WEEE) e must be recycled since the beginning of 2014 (PV Cycle, 2014). Furthermore, innovative business schemes initiated by the industry such as voluntary take-back schemes are currently evolving (Luger et al., 2010; Recyclingbörse, 2013). Apart from that, recent studies also emphasize the importance of developing new overall business schemes such as a "leasing of products or selling functions instead of products" (MacLean et al., 2010). For the case of lithium, Prior et al. (2013) have recently introduced "servicizing" the metal- value chain as a means to shift a product's value from its role as a product itself to the actual service it provides to the society. This would imply a considerable change within producer-consumer relationships, as well as "a fundamental shift in the governance" of metals.

4.2.2 Strategies as a means to develop a "common basis"

Our findings, including the experts' statements, confirmed our previous assumption of the lack of a common basis or objective of approaches, but they also offered possible ways of dealing with the issue: Strategies, addressing the major challenges and incorporating various levels of action into one over-arching bundle of measures, were regularly mentioned also by the experts as a possible means to balance and align governance and industry measures, including research funding programs etc. (see also Wäger et al., 2012). A common regulation for sustainable use of critical metals would, however, also pose various challenges. At the foremost, strategies would have to include, embed and coordinate a high diversity of aspects and surrounding conditions. These include differences in national and international regulations and different political and societal systems and settings, but also the overall complexity of life cycles and often highly different conditions applying to each critical metal (Wäger et al., 2012).

Looking into current strategies and strategy making processes illustrates how different countries and institutions approach metal criticality. While in the last years various strategies and programs have been set up to reduce the criticality of metals (such as the German resource strategy (BMWI, 2010), the EU Raw Materials Initiative (EC, 2008) and the US Critical Metals Strategy (DOE, 2010)), most of them only partially reflect the criteria we identified as vital.

In Germany, both the German resource strategy as well as the recently approved Resource Efficiency Program (ProgRess) emphasize the importance of supporting such common resource- related activities through political measures and guidelines. ProgRess also states that success in taking the measures developed in the program will largely depend on proactive activities from, and cooperation with, various societal groups and stakeholders (BMU, 2012). The measures formulated in the German Resource Strategy reflect the criterion of combined state and economic measures, national and international cooperation, as well as supporting exploration, primary production, material efficiency and recycling processes (BMWI, 2010). The ideas for "flanking measures", however, focus on foreign trade and affairs, and on supporting the private economy and research, rather than on actual regulation.

The EU strategy focuses on three issues: (i) achieving an equal access to resources for EU countries as for other countries, (ii) setting a frame to ensure a consistent supply with resources and (iii) lowering the European resource use through resource efficiency and recycling. It therefore embraces the aspects of international cooperation, frame-setting and securing primary metal supply, and also calls for stricter EU-wide regulation (EC, 2008), but is somewhat lacking concrete ideas on how to bring technologies and governance together, which would go beyond the setting-up of research support programs for technological innovation.

The US Critical Metals Strategy similarly emphasizes the importance of international cooperation and the need to set up structures for diverse metal supply sources, but also mentions two more vital pillars: research with a focus on the development of substitutes for metals with supply risks, and recycling, re-use and resource efficiency that may be achieved through increased research efforts, as well as policy measures (DOE, 2010). Quite a few of the measures identified in this article can be found in the suggestions made in the US strategy, such as policies for directing metal recovery and establishing a working recycling infrastructure. However, it does not give explicit information on how to balance state and private economy measures for that purpose.

5 Conclusion

We identified a high quantity of existing approaches and ideas in terms of technology options and governance interventions that target indium criticality and contribute to its more sustainable use. We analyzed the impacts these approaches have on each other and how they interrelate, identified consistent sets of possible future developments of the latter, and evaluated them regarding their consistency and plausibility given changing environments. The analysis showed that business-as-usual is not an option in times of an increasing indium demand. Moreover, neither focusing on one life cycle phase (as in the recycling scenario) nor on a specific hierarchical level or stakeholder (as in the stringent regulation scenario) would provide for a long-term solution. Rather, measures will first have to target the whole life cycle. Treatment of EoL products and secondary indium production should be increased through the improvement of technological processes. Here, particular attention must be paid to research and development practices (R&D) supporting innovation. Similarly, a provision with primary metal needs to be secured by developing more efficient and eco-friendly exploration and mining processes as well as by international cooperation in trade. Losses over the life cycle need to be minimized by optimizing interfaces of life cycle stages.

As a by-product of other metals, indium production rates are not directly linked to rates of supply and demand. Therefore, measures taken by the state are a necessary instrument to direct indium production and use. But the possibility to set up regulations that are legally binding may be limited in globalized supply chains. Thus, state bodies must also foster the involvement and cooperation of different stakeholders like NGOs and the private industry along the indium life cycle.

In order to sensibly regulate resource use in the case of indium as well as other critical metals, further research is shown to be necessary for a closer examination of the surrounding legal, political and economic systems and other factors determining their use. Especially, the metals' applications, the availability of substitutes for the different indium-containing products, the market dynamics and societal criteria, as well as the question of what role each of the hierarchical levels play and how measures on different levels could be "coordinated", have not been a part of this study in detail and will therefore have to be addressed. This also stresses the need for further research on the development of comprehensive, integrated, but also specified strategies, reflecting the call for a common basis as well as a balanced relationship of state and non-state measures.

Resource strategies can serve as a valuable means to achieve a more sustainable use of critical metals by coordinating measures for different metals on various geographical and temporal scales. The findings of this study can support strategy building processes by providing a basis to identify and prioritize possible measures, including technology options and governance interventions, and to understand how they interrelate with others. This could contribute to tackling the issue on different scales from local to global, as well as with the necessary balance between state and non-state approaches.

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Appendices

A. Impact matrix

The table shows the impact each of the 16 impact factors has on each other. Assessment was exercised by the study team based on expert interviews and literature, and with the following differentiation:

0	=	no impact
1	=	medium impact
2	=	strong impact

All values of the same row add up to the overall activity measure of the impact factor, all values of the same column result in its overall passivity measure.

App. A. Impact matrix

	Direct impacts	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	Activity
1	Efficiency of mining and refining processes		0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1
2	Product manufacturing efficiency	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	Material efficiency	0	0		0	0	2	0	1	0	0	0	0	0	0	0	1	0	0	0	4
4	Resource efficiency in primary production	0	0	0		1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
5	Exploration methods	0	0	0	0		0	1	1	0	0	0	0	0	0	0	1	1	0	0	4
6	Eco design and life cycle management	0	1	1	0	0		1	2	0	0	0	0	0	0	1	0	0	0	0	6
7	Substitution	0	0	1	0	1	0		1	0	0	0	0	0	0	0	0	0	0	0	3
8	Innovative EoL recycling technologies	0	0	0	0	1	0	1		0	0	0	0	0	0	0	0	0	0	0	2
9	Support programs	1	2	2	1	2	1	1	2		0	0	0	1	0	1	0	1	0	0	15
10	Legislation	1	1	1	2	2	2	0	2	1		2	2	1	0	1	1	0	0	0	19
11	Taxation	1	2	2	0	2	1	2	1	0	0		0	0	0	1	0	0	0	0	12
12	Raw material management	0	0	0	0	0	1	1	1	0	0	0		0	0	0	0	0	0	0	3
13	Monitoring and other data sampling	0	0	0	0	0	0	0	1	1	1	1	0		1	0	0	0	0	1	6
14	Political strategies	0	0	1	1	1	1	1	1	1	1	1	0	1		1	1	1	1	1	15
15	Private industry networks	0	0	1	0	0	2	0	2	0	0	0	0	0	0		1	1	0	0	7
16	Standard setting	1	1	1	2	1	2	1	1	0	0	0	0	0	0	0		0	0	1	11
17	Consumer education and awareness programs	0	0	1	1	0	1	0	1	0	0	0	0	0	0	2	0		0	0	6
18	International institutionalization and global governance	0	0	0	0	0	0	0	0	0	1	0	0	1	1	1	1	1		2	8
19	Good governance and transparency initiatives	0	0	0	1	1	0	0	1	0	0	0	0	1	0	0	1	1	1		7
	Passivity	4	7	11	8	12	13	9	18	3	3	4	2	5	2	8	8	6	2	5	130

B. List of technology options

The table shows the technology options identified from the expert interviews and literature review. They formed the basis for the construction of impact factors. It includes a description of each option as well as an indication to the according reference (literature source or number of expert interview, marked in square brackets).

App. B. List of technology options

	Name	Description/details	Source (literature or interview)
1	Technological innovations for exploration	Methods to find more conventional near-surface deposits, such in greater depths and also unconventional ones	Kesler, 2010
2	Exploration focused on minor metals	Make use of geological knowledge to focus on finding (high-grade) minor metal deposits	Hagelüken and Meskers, 2010; [1]
3	Clean technologies	Use of environmentally friendly techniques for the reduction of waste and water and energy demand (dry processing, more breakage already during blasting, energy-efficient grinding, water treatment and re-use, use of alternative processing routes, e.g. in situ leaching, increased use of renewable energies,…)	MacLean et al., 2010, Norgate 2010; Ayres 1997
4	Achieve lower-grade removal of ore	Reduce the amount of new deposits by finding ways to remove also the lower-grade material from existing ones (in an economically viable manner)	Kesler, 2010
5	Increase minor metal yields	Install appropriate recovery/separation processes for minor metals	Hagelüken and Meskers, 2010.]
6	Rework historic primary stocks	e.g. stock-piled tailing and slag, unmined parts of ore bodies; develop processes for the exploration and extraction of tailings	Hagelüken and Meskers, 2010; [1]
7	Substitution	Material substitution, i.e. replace indium with other materials	Kesler, 2010; [4] [6] [8]

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App B. List of technology options ctd.

	Name	Description/details	Source (literature or interview)
8	(Material) Efficiency & durability; life cycle management	Lower material demand through a higher efficiency (Wirkungsgrad) of the product, increased material efficiency and a longer product life time	Allwood et al., 2011; [4] [6]
9	Design	Optimized product design to reduce environmental impacts and facilitate a later disassembling and recycling (Eco- design, Design for Sustainability, Design for Urban Mining; Cradle-to-cradle)	MacLean et al., 2010; Wäger et al., 2012.
10	Innovative recycling (pre-consumer)	recycling of sputtering targets, improve re-use of scraps from sputtering chambers	Hagelüken and Meskers, 2010; [1]
11	Innovative recycling (EoL)	special recycling technologies such as for ITO and PV manufacture; techniques to separate indium layer and dissolve in concentrate; improve recovery from EoL such as flatscreens; small-quantity recycling	Hagelüken and Meskers, 2010; [1] [3] [4] [6] [8]
12	Primary production efficiency	higher (direct) yields, e.g. through direct smelting or mechanical pre-processing	MacLean et al., 2010; Hagelüken and Meskers, 2010.
13	Urban mining	or "mining above ground": explore old waste rock piles and landfills (e.g. in the German Harz mountain region)	[6]
14	Increase resource productivity	i.e. use of energy and material efficient technologies, improvements and innovations in production processes; modern procedures for the separation of indium	Sanden et al., 2011; [1]
15	Modern sputtering processes	increased direct yields in sputtering	[1]
16	Treatment of tailings	from zinc production (anode sludge)	[6]

C. List of governance interventions

The table shows the governance interventions identified in the expert interviews and literature review. They formed the basis for the construction of impact factors. It includes a description of each intervention as well as an indication to the according reference (literature source or number of expert interview, marked in square brackets).

App. C. List of governance interventions.

	Name	Description/details	Source (literature or interview)
1	Government stock piles	to mitigate supply chain disruptions	MacLean et al., 2010.
2	Best-of-two-world approaches	e.g. for mechanical pre-processing: combine affordable labor with state-of-the-art recovery processes	Hagelüken and Meskers, 2010
3	Recycling deposits	To be paid on consumer products	Hagelüken and Meskers, 2010; [2] [3]
4	Product leasing	Leasing of products instead of buying	Hagelüken and Meskers, 2010, [4]
5	Sale of functions	Sale of functions instead of products	Hagelüken and Meskers, 2010.
6	Extended producer responsibility, take-back duties	Companies develop strategies for securing their needs through their own EoL streams; serves as an incentive for recyclability of products	[1] [4]

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App. C. List of governance interventions ctd.

	Name	Description/details	Source (literature or interview)
7	Finance recycling costs through legislation	(As market regulation itself would mean ever increasing prices and is therefore not an option)	[1] [3]
8	EU guidelines	WEEE, EoL vehicle directive	Sanden et al., 2011.
9	Closed cycles	Find ways to prevent illegal export and non-compliant recycling processes	[1] [3]
10	Monitoring	Monitor EoL flows, …	[3]
11	Consumer awareness	Instruments to improve consumer awareness for resource issues (ecological footprint, product durability, …), also in schools and professional education	[4] [3]
12	Political agreements & declarations of intent, international contracts	e.g. Stockholm 1972, Agenda 21, Johannesburg 2002, G8, Action Plan of 2003 (Sustainable Materials Management)	Sanden et al., 2011.
13	International Panel for Sustainable Resource Management	Existing since 2007, one of 4 working groups deals with metals	Sanden et al., 2011; Bleischwitz 2008.
14	Support programs for exploration	e.g. for research, subsidies from the state for exploration; structural support (BGR e e.g. geological exploration prior to commercial exploration); tax deductibility of expenditure	[1] [5] [6]; German Resource Strategy (Bundesministerium für Wirtschaft und Technologie (BMWI), 2010)
15	Investing securities and incentives	Incl. KfW approaches (Germany) etc.	[1]
16	Legal regulations for EoL recycling	e.g. see EoL product as a whole and demand indium recycling. Even if it is not the valuable part in a product	[3]
17	Anthropogenic interim deposits	Set up deposits specifically for those materials that cannot be recycled (in an economically viable manner) today and use them as a basis for upscaling at a later point	[1]
18	Political strategies	i.e. politics sets the side rails and defines objectives instead of the concrete way of getting there; e.g. to stop/avoid dissipation	[1] [3]
19	International Resource Convention	Defined as an objective from the German BMU	Sanden et al., 2011.
20	TREMs (Trade related environmental measures)	Resource-related product and production standards/ specifications	Sanden et al., 2011.
21	Obligations to inform	Install obligations to inform about material flows as a pre- condition for market access	Bleischwitz et al., 2010; [5]
22	Dynamic standard-setting	e.g. obligation to use a minimum percentage of recyclates	
23	Taxation & state-sided prioritization of green technologies	Raise taxes on resource-related activities; set up a differentiated value added tax (VAT) system to financially support environmentally friendly products; material input tax to influence consumer behavior; taxation of primary metal use	Bleischwitz et al., 2010, [4] [5]
24	Private law contracts & voluntary self-commitment	Contracts between (private) stakeholders committing to high-quality recycling and a continuous increase of resource efficiency	Bleischwitz et al., 2010
25	Voluntary take-back systems	e.g. PV Cycle	[3] [6]

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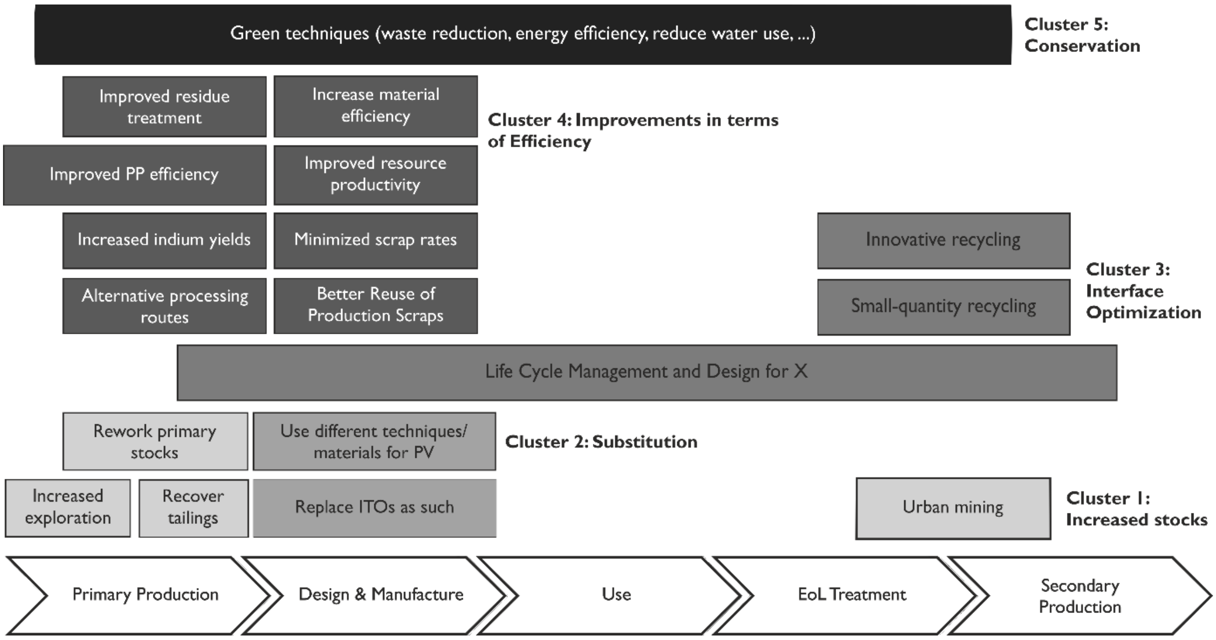
App. C. List of governance interventions ctd.

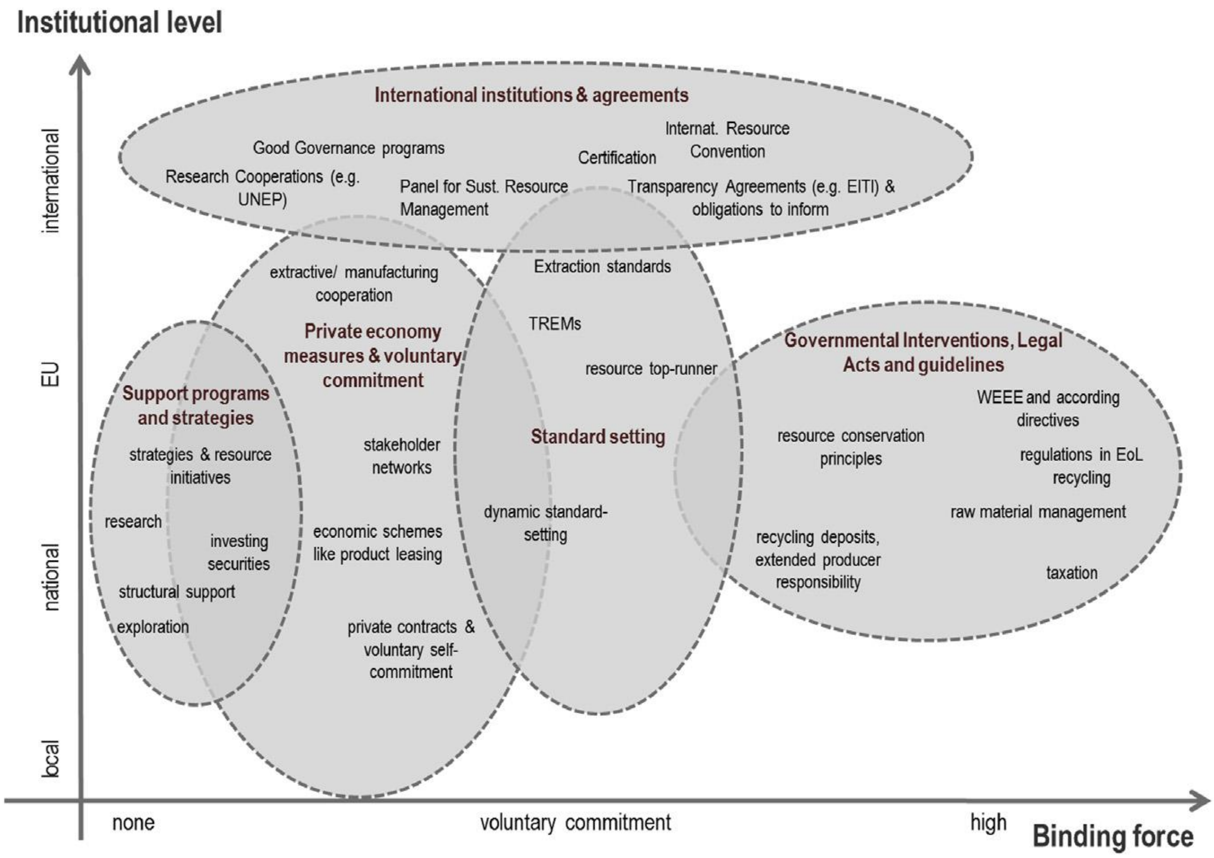
	Name	Description/details	Source (literature or interview)
26	Make use of existing systems	Use existing and established systems, such as for electronic waste return systems, also for the recovery of critical metals	[3]
27	International research approaches	Make common efforts to deal with resource issues, e.g. UNEP	[3]
28	Certification	As with diamonds (Kimberley process)	[4] (rather not relevant for indium)
29	Trade Policy and Law	Such as trade bans	[4]
30	Transparency	Similar to Dodd-Frank-Act: lay open cash flows and payments to prevent corruption	[4] (rather not relevant for indium)
31	Good governance	Programs to enhance good governance principles, esp. in developing producing countries; goal: set up structures to allow for an implementation of minimum standards	[4]
32	Product efficiency standards	Develop specifications for minimum efficiency standards (as with eco-design directive, for resource efficiency)	[4]
33	Cooperations of extractive and manufacturing industry	Match supply and demand data, so each party can adapt accordingly	[4]
34	Resource top-runner	Similar to energy efficiency e apply to resource use (best available product on the market sets the standard)	[4] [5]
35	Resource conservation principles	Implement resource conservation as one of the basic principles in the German BImSchG (related to processes within a company to achieve a sparing use of critical metals)	[5]
36	Use existing legal structures	e.g. set up structures analogous to the German ElektroG for critical metals (LCD, PV)	[5]
37	Raw material management	Principles of use (similar to water)	[5]
38	Extraction standards	Set up specifications for mining practices	[5]
39	Structural and research support	Deutsche Rohstoffagentur: cooperation between government and economy; support research for material efficiency or recovery of indium from production scraps (compare MaRess) make use of support programs in a structured way (targeted support of specific research); IMA Interministerial Committee on Resources with participation of the BDI	[7] [8] German Resource Strategy (Bundesministerium für Wirtschaft und Technologie (BMWI), 2010)
40	Foreign trade promotion	Instruments to promote foreign trade such as (in the case of Germany) such as UFK and investment guarantees, Hermes loans/export guarantees	German Resource Strategy (Bundesministerium für Wirtschaft und Technologie (BMWI), 2010)
41	Research associations and cooperations	e.g. REWIMET e networks of stakeholders with different competencies to achieve efficient and viable product recycling; cooperation of recycler and PV producer	[8]

D Technology option and governance intervention clusters

The images below show the clusters that were built from the various technology options (1) and governance interventions (2).



App. D1. Technology options clusters.



App. D2. Governance interventions clusters.

E. Impact factors and future levels

The table below shows the final set of impact factors and the future levels defined for the scenario-building process. Each impact factor has two future levels, whereas level 1 refers to the state as of today and level 2 represents a (positive) development of the factor as defined in literature or by the experts we interviewed. Information given in italics (bullet points) is not meant to be comprehensive or projective, but aims to illustrate with some practical details, what is meant with both future levels.

App. E. List of impact factors, descriptions and their defined future levels

#	Name	Description	Level 1	Level 2
1	Primary production efficiency	Methods, processes and technologies targeting minimizing losses as well as energy & resource consumption during exploration and primary production (mining and refining)	Conventional exploration; low efficiency for minor metal production, high losses & energy demand	Innovative exploration, high efficiency and recovery, low losses & energy demand ▪ *exploration of high-grade deposits based on geological knowledge* ▪ *application of clean technologies such as dry processing* ▪ *mine greater depths and unconventional deposits*
2	Product manufacturing efficiency & pre-consumer recycling	Methods, processes and technologies targeting minimizing losses during product manufacture and recovering production scraps (pre-consumer recycling)	Low efficiency, medium recycling ▪ *recycling of sputtering targets relatively widespread, but sputtering process itself is very inefficient*	High efficiency, low scrap, high recycling ▪ *increased direct yields in sputtering*
3	Material efficiency	Methods, processes and technologies targeting reducing the (indium) material input per unit while keeping up its functionality	Status quo ▪ CIGS: "light-to-power conversion efficiencies exceeding 20%" (Chirilă et al., 2013)	High material efficiency ▪ *improvements in CIGS e.g. through use of silver, less copper, ...* ▪ *longer product life times*
4	Eco-design and life cycle management	Methods, processes and technologies targeting facilitating recovery and re- use of materials throughout the whole life cycle, including design for urban mining	Medium eco-design, medium product life time	Improved eco-design and recyclability, long product life time ▪ *spread of concepts such as Design for Sustainability or Urban Mining, and Cradle to cradle, allow for an optimized product design and facilitate later disassembling*
5	Substitution	Methods, processes and technologies targeting finding materials to substitute indium in products while keeping up their functionality	Status quo: substitution rare *"The price volatility of indium and supply concerns has promoted the development of ITO substitutes, indium's main use, although currently there is no available alternative material for this." (SETIS EC 2014)*	Various possibilities for substitution, e.g. ▪ *antimony tin oxide coatings for ITO in LCDs* ▪ *carbon nanotube coatings for ITO "inflexible displays, solar cells, and touch screens"* ▪ *PEDOT Poly(3,4-ethylene dioxythiophene) for ITO in flexible displays and organic light-emitting diodes*

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App. E. List of impact factors, descriptions and their defined future levels ctd.

#	Name	Description	Level 1	Level 2
				▪ *graphene quantum dots for ITO in solar cells and possibly LCDs* ▪ *"adhesive zinc oxide nanopowder to replace ITO in LCDs"* ▪ *Gallium arsenide for indium phosphide in solar cells* *(all based on USGS 2013)*
6	Innovative EoL recycling technologies	Methods, processes and technologies targeting an innovation of recycling and treatment of EoL products in order to increase secondary production stocks, including urban mining technologies	Very low EoL recycling rates ▪ *basically no post-consumer recycling (< 1%) of indium-containing products (UNEP 2011)*	High EoL recycling rates viable ▪ *recycling of solar panels becomes economically viable due to higher amounts and improved processes such as wet mechanical processing (compare e.g. Photorec research project or (Berger et al., 2010))*
7	Support programs	Instruments of financial and structural support to encourage research and investment, nationally and internationally, and by the state or state-affiliated organizations targeting new technologies, exploration methods, etc.	Status quo: singular activities	High and well-structured support ▪ *e.g. research funds targeted at material efficiency etc.* ▪ *structured use of support programs* ▪ *strong impact of research associations like REWIMET*
8	Legislation	Instruments using legal/binding force to influence resource use and disposal on different levels, through legal acts on state level or directives to be implemented by the states at supranational level (such as the EU)	Status quo: singular regulations	Well-marked legal system for resource conservation and critical metals ▪ *e.g. legal regulation to demand indium recycling, not just weight-based recycling objectives* ▪ *use existing structures to apply to critical metals as with the German ElektroG*
9	Taxation	Instruments aiming at influencing resource use through financial incentives or hurdles, posed by the national state	No taxation	Well-marked taxation system ▪ *e.g. tax deductibility of exploration expenditures* ▪ *raise taxes on resource-related activities, taxation of primary metal use*
10	Monitoring and other data sampling	Instruments used to enhance knowledge on indium stocks and flows towards optimizing and organizing the indium life cycle, nationally and internationally, and realized by the state and its organizations, or an international cooperation of these.	Monitoring low and unstructured	Broad and centrally organized monitoring ▪ *i.a. monitoring of EoL flows* ▪ *obligations to inform are being installed on a broad basis as a precondition for market access*

ctd. on next page

App. E. List of impact factors, descriptions and their defined future levels ctd.

#	Name	Description	Level 1	Level 2
11	Political strategies	Instruments defining objectives and desired developments for a certain area or sector, nationally or internationally, and by the state or supranational organizations. They might target private industry, consumers or any other possible stakeholder.	Status quo: singular strategies ▪ *national strategies with different foci and objectives such as in Germany, the EU and the US*	Elaborate and ambitious strategies esp. for critical metals ▪ *strategies are harmonized in between the various levels and have a clear focus on critical metals*
12	Private industry initiatives and networks	Instruments targeting increases in resource efficiency, recycling rates or a minimization of metal losses throughout the whole life cycle, nationally and internationally, initiated by the private industry through voluntary commitment or company networking	Status quo: pilot projects	Broad cooperation and implementation of innovative economic systems ▪ *recycling deposits to be paid on consumer products* ▪ *widespread product leasing concepts* ▪ *voluntary self-commitment and establishment of take-back systems* ▪ *certification programs (compare Kimberley process for diamonds)*
13	Standard-setting incl. resource top-runner	Instruments that aim to influence resource use through certification, the definition of standards or other quality criteria, or resource top-runner approaches on a national or international level	Status quo: singular product standards	High standards with explicit reference to metal use ▪ *TREMs (trade-related environmental measures) as resource-related specifications* ▪ *dynamic standard-setting, minimum efficiency standards* ▪ *resource top-runner system*
14	Consumer education and awareness programs	Instruments aiming at raising awareness for resource efficiency, recycling, etc. They can be national as well as international, and initiated by the state as well as different organizations or interest groups	Status quo: no specific programs	Broad campaigns and education ▪ *resource use obligatory part of education programs in school, but also at universities (e.g. engineering) and in professional education*
15	International institutionalization and global governance	Instruments aiming at the creation of a global resource governance regime, i.e. a cooperation of various national states and organizations of any kind on an international level.	Status quo: singular, more general (or very specific) agreements ▪ *Agenda 21, G8 Action Plan of 2003 (Sustainable Materials Management)* ▪ *WEEE, EoL vehicle directive*	Intensive resource-specific collaboration ▪ *establishment of an International Resource Convention* ▪ *prevention measures to minimize illegal export*
16	Good governance and transparency initiatives	Instruments employed to enhance transparency and sustainability of resource production and trade, be it national campaigns or international initiatives, and organized by private as well as state-affiliated organizations	Status quo: singular initiatives exist	High(er) international support, advancement of existing initiatives ▪ *comparable structures as with the Dodd-Frank-Act (transparency)*

F. Full prose scenarios

Scenario 1: Trend extrapolation

Technological as well as governance activities have largely remained at the 2012 levels and foci in the past years. Accordingly, advancements have mainly been achieved in product manufacturing and material efficiency, where technology options had already been in a pilot stage in 2012. Only in recent years, have considerable achievements also been made in innovating EoL recycling, mainly due to activities initiated by the industry and concerned stakeholders trying to cope with insecurities concerning indium supply, as primary production remains conventional and resource-intensive, and highly inefficient for minor metals. Research activities started too late, however, to be sufficiently established to really make a contribution. The formulation of strategies specifically for critical metals and of international agreements on the issue shows its on-going political and societal relevance. Additionally, the state has made its contribution through increased financial support for research on resource efficiency, and also high product standards have played their share. Meanwhile, no strong instruments such as legal regulation, taxation or a mandatory and comprehensive monitoring system have been installed to direct resource-related activities.

On the whole, increased efficiencies cannot fully complement the lack of new primary metal, and due to the current monitoring of stocks and flows, especially when recycling technologies were still inefficient, a great deal of indium has already dissipated or been disposed of at unknown places or where it cannot be retrieved, leading to on-going concerns about supply security on a medium to high level.

Scenario 2: A recycling society

The focus of activities over the past years has clearly been on increasing recycling rates and achieving closed cycles for indium containing products, leading to considerably increased recycling rates of EoL products, but also to an improved efficiency of processes along the whole life cycle of products, resulting in a high efficiency of product manufacturing processes and a high material efficiency. Losses have been considerably reduced through a high consideration of eco-design principles and high pre-consumer recycling rates. On the other hand, the role of alternative technological approaches, such as finding unconventional indium deposits and developing new technologies for exploration, as well as finding ways to substitute indium, has only been secondary: While the exploration of zinc deposits had already been a routine action in 2012, the primary production industry has missed opportunities to achieve improvements regarding the identification of ores with a high indium concentration.

To a large extent, the achievements in the optimization of life cycle interfaces have their roots in the mobilization of industry stakeholders and the civil society. Firstly, intensive activities targeted at the creation of awareness among stakeholders and consumers have led to a reduction of products that are not being recycled because they are being disposed of inappropriately. And ever since resource efficiency issues have become a subject in professional education, they are being largely considered during product design and manufacture. Secondly, also as a consequence of this, in the absence of legal regulations and support from the state, more and more companies are prepared to commit themselves voluntarily to an application of high standards in production and have initiated a variety of networks, in which each partner contributes some expertise to achieving closed product chains and a broad recycling of products that is economically viable. This has become especially relevant for EoL-PV panels that have started becoming increasingly available in recent times. Thirdly, these activities on a lower organizational level are supported by an intensive collaboration of states and actors on an international scale. The state has specifically committed itself to contributing to the closing of life cycles of critical metals in national and international strategies, as well as specified international agreements. Among others, this has led to the implementation of a centrally organized monitoring scheme and resource cadaster.

All of these achievements have brought about a situation in which urban mining is no longer a distant vision, but a phenomenon of every-day life. Nevertheless, as primary production is still low, some recent studies do not see indium among the most critical metals anymore, but concerns about future supply disruptions are still an issue. Additionally, urban mining is still mostly limited to landfills set up in the last decade, as the recovery of material from old landfill sites is connected with such environmental burdens and high costs that it could be established neither politically nor financially, showing that the increased indium demand cannot be covered by recycling alone.

Scenario 3: Stringent regulation

An increased awareness for the future importance of the use of renewable energies in the light of climate change and the visible dangers of nuclear energy has resulted in the national state taking comprehensive and far-reaching measures towards securing indium supplies, largely independent of international developments. Financial and structural support has continuously increased from their 2012 levels. Accordingly, investment securities and loans, as well as research excursions from state-affiliated organizations like the German BGR, prior to company-led exploration of deposits, have contributed to a considerable increase in exploration and higher primary indium stocks. Parallel to this, research activities have been funded heavily and consumer patterns directed towards a closing of life cycles through the implementation of a resource conservation act, as well as legal acts specifically targeted on keeping in-use critical metals within the system, making the advancement of product and production standards, as well as private industry networks, largely unnecessary. Consumer behavior is, on the one hand, directed through awareness creation, but, on the other hand, mostly through exercising pressure on the concerned parties through the implementation of strong governance instruments, creating either financial incentives (like product leasing and recycling deposits) or hurdles (like a tax on use of primary metals) and thereby indirectly "forbidding" resource-inefficient activities. Consequently, large amounts of the primary metal entering the system can be secured throughout the life cycle and recycling rates have increased considerably. The resulting relatively high indium stocks leave no remarkable incentives for substitution, which stagnates at around the 2012 levels. The developments of the last years have also disclosed limits to the directing power of legislation. These become apparent especially in relation to the resource efficiency of primary production processes, where legislation and standards were already quite high in 2012, but due to the broad distribution of indium, processing and refining have remained difficult and resource-intensive. Companies have attempted to further reduce energy and water demand, especially in order to reduce costs.

Scenario 4: A world of cooperation

Activities on all levels have shifted more and more towards cooperation and a joint facing of challenges. On a national level, the state and the private industry share competencies and responsibilities: Ambitious and far-reaching political strategies demonstrate the state's commitment to attaining a sustainable use of indium and other critical metals, setting the side-rails for all activities on the issue and resulting in a fairly strict legal system relating to resource-efficiency and conservation. Additionally, it supports the development of private industry initiatives and net- works by financially supporting them and leaving them the necessary scope for action. Companies have taken the opportunity and set up well-functioning take-back systems and networks, from which all parties involved can benefit. State and private industry have also cooperated in the definition of ambitious product standards and a resource top-runner system positioned at the center of a holistic governance scheme that also includes annual awards for special involvement and successes in indium research, and ac- cording taxes on the use of primary metal and dissipation. Consequently, advancements have been reached at all stages of the indium life cycle. Primary production issues are dealt with particularly at the international level. Industrial and producing states have mutually agreed on some guiding principles for mining indium-containing major metal ores like zinc and other metal de- posits and compensating environmental disturbances, making the mining process more eco-friendly and socially accepted in the concerned regions. International institutions, such as a panel for sustainable resource use, oversee and monitor the developments, reserves and material flows world-wide and also observe the compliance with transparency agreements like EITI, which has been broadly accepted. The disclosure of cash flows through pro- grams like PWYP has further increased transparency and reduced corruption in the mining sector to an all-time minimum. It has also resulted in relatively fair trading conditions for all parties concerned.

Although indium is still considered a rare resource, it is no longer categorized as a highly critical metal, mainly for two rea- sons: Firstly, it lacks one decisive factor for criticality, namely the insecurity of supply due to a high dependence on a few producing countries with relatively intransparent structures. And secondly, the improvements throughout the whole life cycle make the sys- tem adaptable and more resilient towards a varying indium supply, which means that the increased demand can be met to continuously use indium for appliance in future technologies like PV technologies and thin-film coatings.

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4.4 Towards a more sustainable metal use – Lessons learned from national strategy documents

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Abstract

There is urgent need to change the way we make use of non-renewable resources, especially metals, to sustain their availability for vital technologies associated with achieving change towards sustainability, but also to minimize negative impacts and to achieve a fair distribution of the wealth and burdens associated with their production and use. Especially public actors (state governments and administrations) have recently formulated strategies as a means to guide action fostering these goals. Yet, these strategies are very different in their character, which makes it difficult to compare them and learn how to best design strategies for a given context to contribute to the necessary change. To approach this question, we analyzed 37 national mineral resource-related strategy documents worldwide concerning their contextual conditions, motivation, and objectives. Following the general inputs for transition strategies (current and target state, transition strategy), we identified four clusters of strategy documents that share similarities in their approaches and support the development of specific recommendations for future strategy design in terms of both content and process. Designing strategies with a clear structure that interlinks a systems-based description of the current state, a clear vision (oriented at sustainability principles) and a sufficiently differentiated but at the same time flexible transition pathway improves their potential to contribute to more sustainable metal production and use.

1 Introduction

Metal availability is a precondition for change processes like the transition to a post-fossil society, calling not only for an energy transition but also for a material transition, both of which are closely linked (Giurco et al., 2014; Schindler, 2016). However, there is little doubt that we need to change the way we make use of metals in order to (i) minimize negative impacts along their whole life cycle, (ii) sustain their availability for future generations and (iii) achieve a fair distribution of the wealth and burdens associated with their production and use (Giljum et al., 2014; Gordon et al., 2007; Norgate and Rankin, 2002; Petrie, 2007; Prior et al., 2012; Tilton, 1996; United Nations Environment Programme (UNEP), 2012). A multitude of studies has analyzed potential supply risks and long-term availability of metals for these future technologies (Buchholz and Brandenburg, 2018; Elshkaki et al., 2016; Grandell et al., 2016; Kesler, 2007; Moss et al., 2013; Watari et al., 2018). Studies have suggested a variety of possible solutions to tackle these supply risks as well as other challenges associated with unsustainable metal production and use (Ali et al., 2017; Bringezu et al., 2016; Helbig et al., 2017; Henckens et al., 2019, 2016). Here, *metal production and use* refers to the complex of processes along the metal life cycle including extraction, concentration and purification, transport, product design, use and End-of-Life (EoL) treatment and recycling (Hagelüken and Meskers, 2010; Kümmerer and Clark, 2016; van Berkel, 2007). As depletable materials, metals should be used rather than consumed. This emphasizes the need to minimize dissipation along their life cycle (Schindler, 2016).

Besides other actors, mainly public institutions or administrations have reacted to these challenges by formulating strategies to guide future resource use. Strategies - defined *as 'a plan of action designed to achieve a long-term or overall aim'* (Oxford Dictionary, 2018) - are a way to formulate (and publish) objectives for intended change in any form from general ideas to concrete measures. Also for the case of public resource strategies, they are very diverse e.g. in terms of regulative, spatial and temporal scale, content, focus and degree of concreteness. At the same time, they share the common element of 'looking ahead' instead of largely 'regulating the status quo'. This makes them particularly suitable for understanding motives and future-oriented ways of thinking. Therefore they are considered key instruments for tackling the complex and interlinked challenges of metal supply and demand (Helbig et al., 2017; Wäger et al., 2012; Weiser et al., 2015) and meeting criticality concerns (Achzet and Helbig, 2013; Graedel et al., 2015a; Kümmerer, 2016). The threat of supply disruptions may hinder economic development and the implementation of environmentally friendly technologies (Font

Vivanco et al., 2017). At the same time, absolute material consumption may continue to increase, while absolute decoupling and an overall reduction would be necessary (Giljum et al., 2014; Kümmerer, 2017).

It is still an open question how strategies need to be designed to foster a more sustainable metal production and use. Existing studies on this issue either focus on a specific aspect like recycling or criticality or often analyze a selection of strategies or countries in a qualitative manner (Barteková and Kemp, 2016; defra, 2012; Gumley, 2014; Hilpert and Mildner, 2013). A broad exploration of strategy documents that considers the existing heterogeneity of strategies as well as underlying patterns of approaches to govern resource use is missing to date. Therefore, we investigated (i) the similarities and differences in existing strategy documents, and (ii) patterns across these strategies to determine, how motivation and contextual conditions influence the design of strategic actions. Our over-arching research objective was the identification of general principles and patterns we can use to formulate recommendations for the design of future strategies as impactful components of the policy environment addressing sustainable metal production and use across levels and scales.

We approached the issue through four main steps as illustrated in Figure 1, i.e., developing a literature-based analytical framework, mapping and coding strategy documents, analyzing patterns, and contextualizing the results.

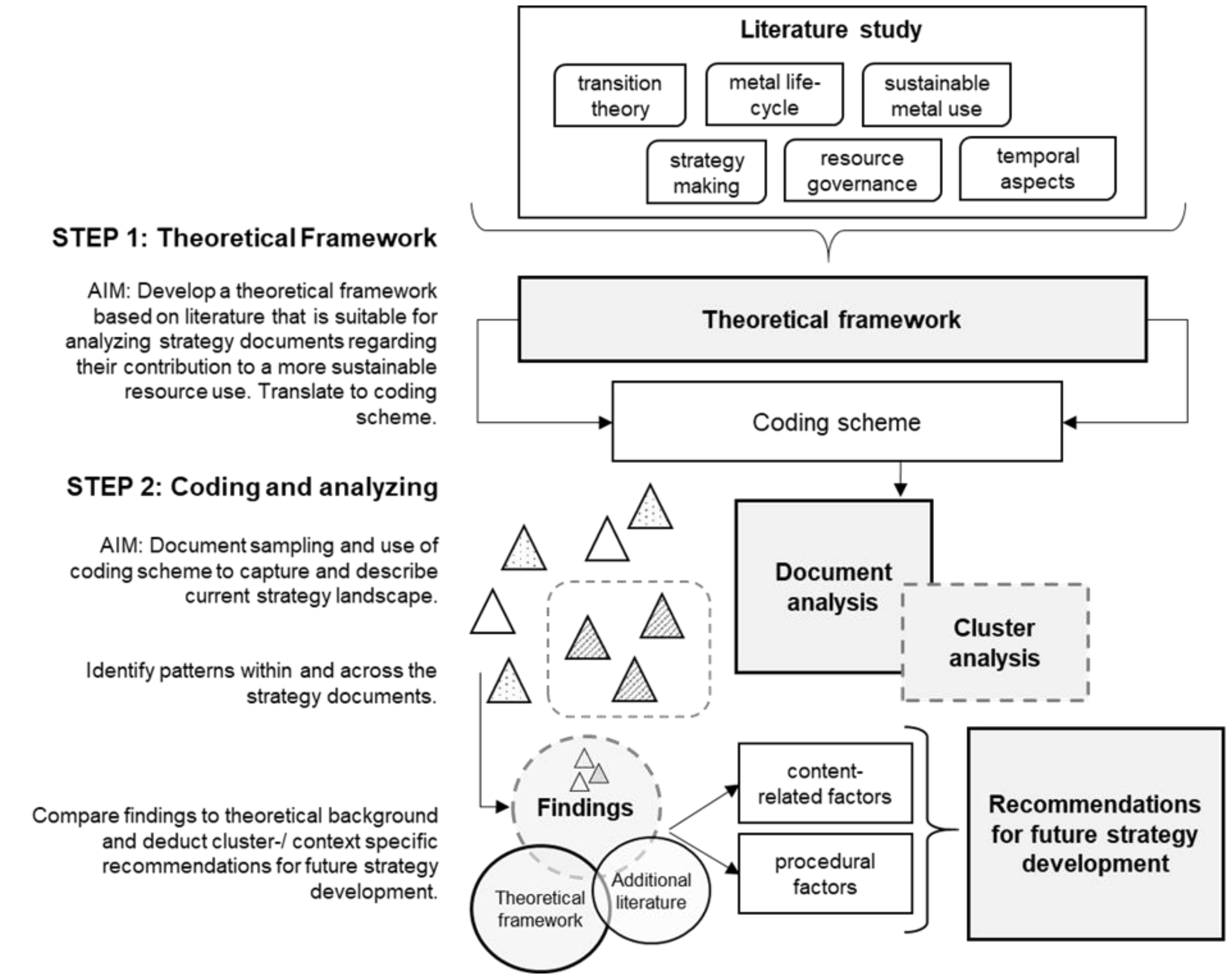

Fig. 1 Schematic overview of the paper.

We particularly focused on temporal aspects and sustainability, respectively, since we found that for the purposes of our analysis each category had specific implications for each of the two perspectives.

2 Research design

The following sections describe our approach relating to the main steps of our analysis as depicted before. A detailed description of all steps, including selection criteria and details on the statistical approach, can be found in the supplemental files (Annex 1).

2.1 Theoretical framework (Step 1)

Our strategy analysis follows the approach of Wiek and Kay (2014), who state that three inputs are critical for the formulation of a sound transition strategy (see Fig. 2):

- A system-based understanding of the **current state** ("where are we now").
- Goals and objectives, summarized as desired **target state** ("where we want to be in the future").
- The **transition strategy** , i.e., a sequence of effective actions for reaching the target state (Raskin et al., 2010). A **theory of change** forms the basis for developing such concrete actions by defining the main points of intervention as well as mechanisms to be applied to bring about the intended change ("how do we transition from [...] to [...]") (*also compare* (Raskin et al., 2010) *for the guiding questions for each input).*

We developed a coding scheme for the purposes of the analysis that links to this conceptual model of strategy inputs. The review criteria are based on literature research (see references and sources in the coding scheme in Annex 3) as well as through iterative adaptions throughout the strategy analysis process (e.g. adding strategic measures that were often occurring in the strategies, detecting specific groups of motivational factors).

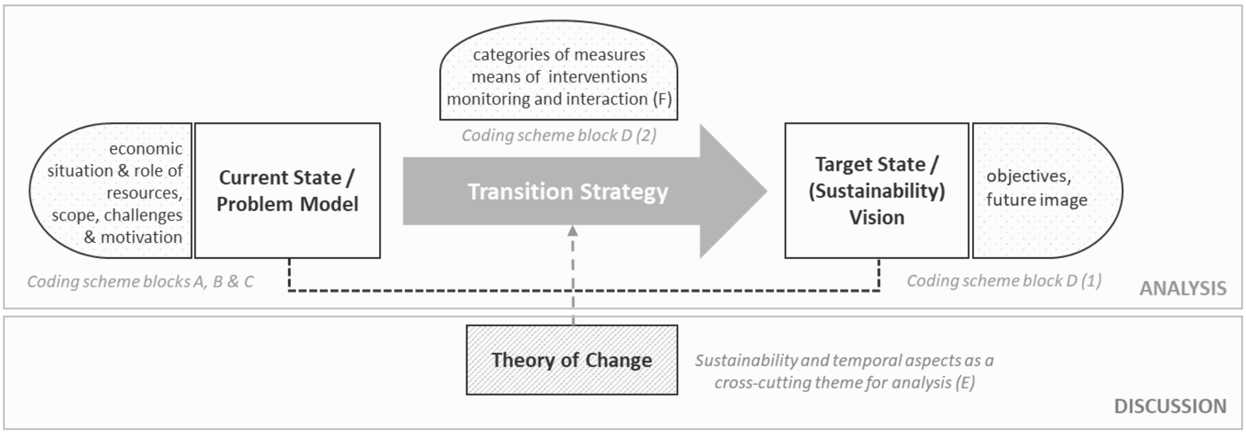

Fig. 2: Conceptual model of strategy inputs following (Kay et al., 2014), and translation into categories for strategy analysis (blocks within coding scheme). Annex 3 depicts the resulting coding scheme.

For *general information* on the strategy document and issuer's background, we sampled document details such as issuer data, year of publishing, and document length.

For the *current state (problem model)*, we collected economic data on the role of resources for the national economy (A), information on the scope and overall approach such as organizational issues, temporal aspects, or coverage of life-cycle phases (B) as well as information on the initial situation, challenges and motivation (C).

For the *future state*, we sampled information on objectives, an overall vision statement, and future needs mentioned in the strategy (D 1).

For the *transition strategy*, we collected and differentiated categories of measures, the level of concreteness, overall means of intervention and monitoring (D 2) as well as information on referrals to processes on other regulative levels or fields of action (F).

For assessing the strategies with regard to their contribution to a transition towards a sustainable target state, we applied various sustainability criteria and temporal aspects as *crosscutting* perspectives throughout the analysis (E). This includes the systemic and temporal effectiveness, the overall framing and rationale, and drivers for unsustainable resource use.

Our assessment of strategies, therefore, differentiated (i) systemic principles for assessment, (ii) temporal aspects pointing towards effectiveness over time, and (iii) principles for judging sustainability aspects in metal production and use.

(i) We differentiated the various <u>means of interventions</u> suggested in the strategies according to Abson et al. (2017) and Meadows (1999) as shallow or deep leverage points. *Parameters and feedbacks*, which represent more shallow leverage points, and *design and intent*, which include the deeper leverage points and are considered by Meadows (1999) to be more effective to bring about system changes.

(ii) The Transition Management Cycle presented by Loorbach (2010) proposes a <u>potential hierarchy of actions</u> (Weiser et al., 2017b) <u>to be considered regarding temporal effectiveness</u>. Strategic, more "sustainable" and long-term goals, which target deep leverage points, may serve as an overall reference for tactical and operational, rather mid- or short-term actions, potentially targeting more shallow leverage points, but leading to quicker success (Loorbach, 2010).

(iii) We differentiated three sustainability rationales employed throughout the documents:

- *"Sustained resources":* addresses sustainability in the sense of "mineral resource sustainability" (compare e.g. (Mudd, 2007)) and/ or sustaining (economic) development
- *"Operating sustainably":* addresses sustainability in the sense of "environmental costs or resource intensity" of resource extraction and use throughout the whole life-cycle
- *"Contribution to Sustainable Development":* addresses sustainability in the sense of resource use contributing to sustainable development (including e.g. equity, well-being, …))

For providing a more differentiated picture to what extent and in which manner these rationales are present in strategies, the work of Moran and Kunz (2014) serves as a point of reference to assess the sustainability potential of the approaches chosen in the strategies. They developed a way to track progress towards minerals and energy sustainability from two different perspectives. On the one hand, they approach progress from the perspective of achieving sustainable development through equitable distribution of value by defining four equity conditions (Future needs met, Satisfied receiving countries, Profitable discovery & transfer agents, and Prosperous supply countries) that should be equally addressed. On the other hand, they assess the operating side by defining four stages of maturity of activities that can lead operations from "Stage 1: Solely profit maximizing" via "Stage 2: Efficiency focused" and "Stage 3: Integrating by connecting" to "Stage 4: Adaptable & resilient".

Having introduced a perspective for assessing the strategic orientation of the strategies, we further analyzed, whether the strategy documents address sustainability issues raised by each of the 17 Sustainable Development Goals and to what extent they target drivers of unsustainable resource use for improving their strategic orientation towards sustainability.

We followed Hirschnitz-Garbers (2016), who define four sets of drivers for unsustainable resource use that strategies would need to tackle in order to address "transformation" of resource use patterns towards more sustainability. These are (i) behavioural and informational, (ii) policy and regulatory, (iii) socio-economic and (iv) technological and infrastructural. (The drivers are further explained in the coding scheme in Annex 2).

2.2 Coding and analyzing strategy documents (Step 2)

We generally followed the steps of a structured literature review as formulated by Luederitz et al. (2016), but adapted the approach to the specifics of analyzing policy documents in a more exploratory manner. First, we gathered the data and selected the final set of documents to be analyzed. We selected policy documents that were published in English and either related to mineral resources in general or to metals or a specific group of metals in particular, which we found through a search string-based Google search (see Annex 1 for a list of search strings). Second, we performed the actual review and analysis of documents by applying above theoretical perspectives. We followed a quantitative content analysis (Neuendorf, 2017; Neuman, 1997) approach and evaluated the frequency of the resulting codes to analyze the strategy documents with respect to their (aspired) contribution to sustainable resource use and the changes they intend to initiate. Third, we analyzed the documents statistically via cluster analysis and multiple correspondence analysis (MCA) using the statistics software R (R Core Team, 2018) to identify groups of countries with similar patterns in their strategic approaches. Finally, we interpreted and discussed the results by highlighting the three main characteristics of each strategy to serve as the basis for policy recommendations.

3 Results

The final sample of documents we analyzed consisted of 37 documents from 35 different countries (see Annex 4 for a full list of documents). The strategies in our sample do not share a common structure and vary in length from two pages (Austria and Japan) to 202 pages (Kyrgyz Republic). All of them were issued through a ministry associated with mining, resources or the economy or similar governmental institutions. The addressee is rarely clearly stated; while some documents are designed in an illustrative way with information boxes, images etc., others have text only and are formulated similar to a bill or resolution. In 16 cases, it is explicitly mentioned that the development process included some kind of stakeholder involvement or participation through e.g. consultations or stakeholder dialogues.

Strategies in the sample vary highly in their structure, scope, focus and the aspects of the resource life cycle they cover. There is a focus on mineral resources in general and on the first stages of the resource life cycle. Only few strategies cover more than two life-cycle phases or the interlinkages between phases.

The following sections present the main findings of our analysis by first illustrating the clusters we could identify (3.1) and then giving detailed information that relates back to the three key inputs of transition strategies: Current state, future state, and transition strategy (3.2).

3.1 Clusters of strategy documents

Despite the large heterogeneity of strategy designs in our sample, we could identify several relevant patterns within as well as across strategies. The exploratory cluster analysis revealed five clusters of documents with shared characteristics (see Annex 5 for cluster dendrogram). The MCA generated a similar view on the data regarding these clusters and, in addition, provided indications on variables distinguishing the clusters from each other (see Fig. 3). Namely, the focus on specific steps of the product life-cycle and the sustainability understanding are the decisive dimensions in differentiating the strategies into clusters. Although these exploratory methods do not explain all variance in the data, they could still support our understanding of the data. We made sense of the statistical results by examining the relevant code frequencies manually with respect to the proposed clusters. This process confirmed that these cluster are a reasonable perspective on the data for identifying patterns that could aid our analysis of strategies and allowed to determine representative names for the individual clusters. (Each of the clusters is described below. A list of countries belonging to each cluster can be found in Annex 4.)

The graph highlights the main gradient on the x-axis from strategies focusing on early life-cycles phases (exploration and primary production) to recycling and resource efficiency and finally product design and consumption. The graph further illustrates the second gradient between the strategies that reflects the three sustainability rationales we applied in our analysis (see 2.1). Aspects that strategies do not cover, e.g. not using the term sustainability, not mentioning health aspects etc., mainly characterize the very top of the y-axis. Towards the bottom, the focus shifts from securing supply to averting negative effects of mining to active contributions to sustainable development such as participation and distribution. To some extent, the clusters also reflect geographic proximity, i.e. they show not only the heterogeneity of the initial (economic) situation in the nation states, but also some degree of regional (socio-cultural or political) influence. This indicates that historical and political developments influence a strategy's specific "mind-set". This result is especially striking since we did not explicitly include any parameters for geographic position, political situation or similar aspects in our analysis[2].

[2] Three documents form a cluster that is separate from all others in the MCA bi-plot. We refer to this group as "outliers" (group 0). Their position in the graph is separate from all others not because their approach is explicitly different. Rather, the overall document structure and set-up differ considerably. The documents in group 0 are comparatively short or less detailed when it comes to defining concrete measures, making an in-depth analysis of many of our variables impossible, so the cluster is mainly characterized by not covering aspects (e.g. not specifying challenges, not describing the initial situation, not calling for fiscal measures). The one for Japan is merely a strategy announcement, since the original version is in Japanese, and Austria has not one but two different (short) documents, which both classify as "strategy" following the selection criteria, but have slightly different foci and approaches.

Table 1 summarizes the main features that differentiate the four clusters of strategic approaches that are explained in more detail in the following.

Table 1: *Summary of clusters*

Cluster no. and name (amount of documents in the sample)	**Main characteristics of issuing countries regarding economic situation, i.e. supply and demand // geographic specifications**	**Focus // sustainability rationale**
I. Upscaling exploration (9)	rather resource-rich, often with large newly discovered reserves and/ or still unexplored areas, high demand // highest share of Asian countries	focusing on exploration and trade // sustained resources
II. Mining for Development (12)	rather resource-rich, economically weaker, low demand // includes the majority of African countries	focus on primary production, concentrate more on mining than exploration // operating sustainably, contributing to sustainable development
III. Our Resources for our Industry (7)	rather resource-rich and rather economically strong, high demand // European, plus Canada	also target later life-cycle stages // operating sustainably
IV. Closing Cycles, securing Supply (6)	less rich in resources, but economically strong with a high demand // Europe and US	addressing all life-cycle phases rather evenly

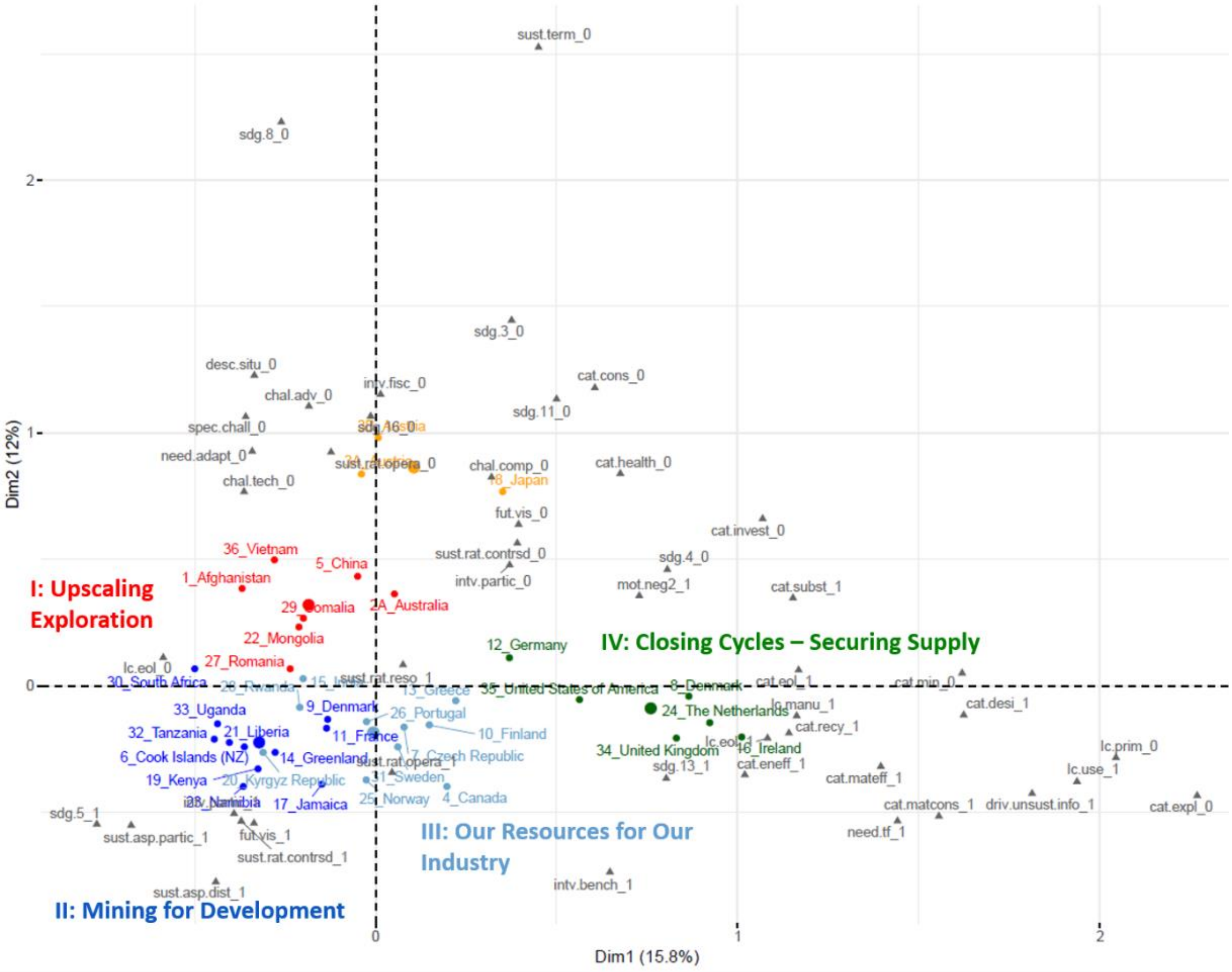

Fig. 3: Bi-plot showing the results of the multiple correspondence analysis (MCA) with the four clusters of countries (group of outliers in yellow)

3.2 Characteristics of strategy documents within and across clusters

In the following, we illustrate and discuss these differences concerning first sustainability as cross-cutting issue, and then the current and future state and the transition strategy (cf. 2.1 Theoretical framework and resulting coding scheme (Annex 3)).

3.2.1 Sustainability (cross-cutting, and block E of the coding scheme)

Existing strategies largely seem to fail to integrate sustainability principles (as developed in our theoretical framework) comprehensively into their suggested actions. While sustainability is mentioned (as a term) in most of the documents in our sample, there is no shared understanding of the concept, and it is not the prime objective in most of them. Rather, sustainability is operationalized in the sense of long-term availability and lacks a comprehensive approach towards addressing drivers of unsustainable resource use. Only two strategies are not mentioning sustainability as a term. On the other end, only six documents offer a definition for sustainability that they employ throughout the document. Definitions range from the Brundtland definition (WCED World Commission on Environment and Development, 1987) or similar conceptions to sustainability in the sense of aligning economic, ecologic and social aspects, and to a resource life-cycle perspective with a focus on recycling.

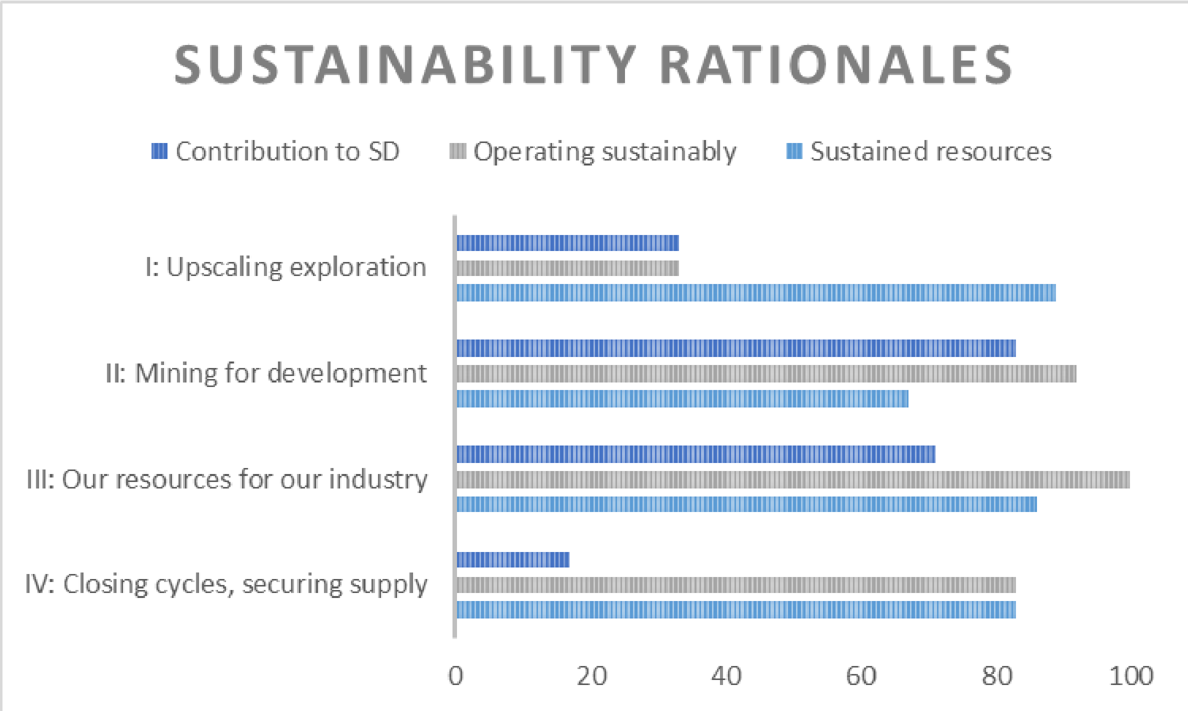

Fig. 4: Share of strategy documents applying each of the three sustainability rationales in the four clusters of approaches

Rationale: The overview in Fig. 4 illustrates the use of sustainability rationales across the country clusters. All countries put some emphasis on sustaining resources and keeping them available in the future (this is least dominant in cluster II). Operating sustainably plays an important role in all clusters but cluster I (upscaling exploration). Contribution to sustainable development is an issue mainly in clusters II and III. Cluster I shows a clear focus on sustained resources, while in cluster IV, countries are comparatively neglecting the aspect of resources contributing to sustainable development.

Similarly, strategies also only partly tackle the goals and challenges raised by the SDGs (see Annex 7 for an illustration of SDG coverage). Seeing the links to metals, surprisingly few strategies deal with issues of climate action (SDG 13) or affordable and clean energy (SDG 7), and regarding responsible consumption and production (SDG 12), they tend to focus on (environmental) standards for industrial processes instead of changes in consumption patterns.

Drivers of unsustainable resource use (as defined by Hirschnitz-Garbers (2016)): Socio-economic aspects are mentioned most frequently, followed by technological and infrastructural causes and policy and regulatory drivers. Behavioral and informational drivers are mentioned in just five of the strategy documents (Denmark, Ireland, The Netherlands, Portugal and UK). In all of them, a lack of information or knowledge is linked to deficits in the end-of-life or secondary production phase. The documents in the sample rarely addressed other aspects often associated with sustainability such as justice and equity. Among those that did, business ethics issues were most frequent, followed by participation, distribution and well-being, and just two documents mentioning resilience, precaution or adaptation and issues of justice and equity.

3.2.1 Current State (blocks A – C of the coding scheme)

Scope and life-cycle phases: The largest part of documents deals with mineral resources in general, with only few being less specified (i.e. raw materials or natural resources), or dealing with metals or a specific group of metals such as rare earth elements. Turning to life-cycle phases, a large majority of strategies covers exploration & primary production (35) as well as transport and trade of commodities (30). Considerably fewer strategies deal with product design and manufacture (7), product use (5) or end-of-life and secondary production (13). Only 11 strategies in total explicitly deal with interrelations and interdependencies between life-cycle phases. Only two documents (The Netherlands and the UK) cover all life-cycle phases. A majority of 23 documents focuses on two phases, which are usually exploration & primary production and transport & trade of commodities. Three strategies (Australia, Denmark (Arctic) and Greenland focus solely on exploration & primary production. The coverage of life-cycle phases varies considerably in the defined clusters: Clusters I and II have a clear focus on primary production, cluster III includes secondary production, but ignores the product phase, and cluster IV is the only one covering interrelations and the product phase, but ignores transport and trade.

Temporal scope: The temporal scope also varies considerably throughout the strategies in terms of (i) the date of issuance and (ii) the temporal extension from issuance to target year or most distant year mentioned in the document. Most strategies, however, have been issued around 2010 to 2014 and have an average extension of approx. 10 years (based on those strategies that do have a defined date of issuance and target year). 18 of the strategy documents are explicitly referring to historical information and long-term developments dating back 15 years or more.

Initial situation: The current state is described to varying degrees of detail and mostly based on economic data (e.g. estimates for demand and supply). The description of the current state is often driven by recent events (e.g. geopolitical developments) rather than by historical developments. Strategies generally state the challenges they aim to address, most of which relate to market-related challenges and resource criticality.

Challenges named: The share of documents stating market-related challenges (i.e. resource criticality issues such as restricted access, dependencies, competition) is comparatively high, while resource depletion (i.e. resource scarcity) is of lower relevance. Most documents refer to adverse (social or environmental) effects of raw material production and consumption; 25 strategies also list technological challenges, such as in recycling or mining in great depth. Other challenges named several times include child labor and a lack of skilled workforce, land use conflicts and indigenous rights, or a lack of (government) capacity, missing data or political instability. Above that, the future of artisanal and small-scale mining is an issue in several documents.

Motivation: We identified five overall "types" of motivation that prevailed throughout the documents we analyzed (see coding scheme in Annex 3):

1. Seizing opportunities 1: New markets and technologies
2. Seizing opportunities 2: Demand fueling local mining industry
3. Seizing opportunities 3: Governance and stability
4. Averting negative effects 1: Progress for competitiveness
5. Averting negative effects 2: Preparing for disruptions

While market developments and competition, political changes or technological innovation seem to have triggered the majority of strategy formulation processes, motivation changes slightly among clusters. Being prepared for potential market disruptions (type 5) is the prevailing motivator for strategies belonging to cluster IV, while (sustaining) competitiveness (type 4) is an issue in the other three clusters, which have a closer link to mining. Similarly, in the resource rich (often Global South) countries of clusters I and II, which focus on exploration and mining, increasing demand (type 2) is seen as an opportunity rather than a threat.

3.2.2 Target state (block D 1 of the scheme)

Visions: Most vision statements within the sample emphasize the role of mining and resources for economic growth. A transformation of resource use patterns, however, does not seem to be in the focus of what is defined as desirable future state. While many express some urgency to act, few mention a need for transformation to sustainability of overall patterns of resource use. Strategies are set up mostly to guide national policies on a more abstract level. Most documents acknowledge the need to take on a long-term perspective on issues of resource use as well as continuous supply, which contrasts with the actual, often rather short time frames the strategies have.

A total of 18 strategy documents explicitly states a vision. In those vision texts, the focus is on mining and economic growth, but local, environmental and social aspects are mentioned in similar frequency. Most countries take on an inward-looking, national perspective, with only few strategies declaring their desired position with regards to or in comparison with other nations (e.g.: attracting investment and finding international partners, living up to international standards, being competitive; but also: being a global or EU leader). More than half of the visions focus on mineral production as leverage for socio-economic development and its positive impact on people. Sustainability is explicitly mentioned in 12 of the visions, mostly through expressing the need for balancing economic with environmental and social issues (plus cultural or territorial issues mentioned by some). Governance and institutional capacity building as well as a functioning regulation are further aspects mentioned in several visions.

Objectives: The text passages expressing the strategies' objectives inform (i) where the thematic focus is set, and (ii) how the strategies are meant to take effect. Similar to the vision statements, the thematic focus is mainly on economic issues, but also on governance-related questions (including decreasing governmental involvement) and on improving the overall performance of the resource industry regarding environmental and social issues as well as knowledge exchange and partnerships. Strategies are in most cases meant to shape, frame or guide national policy principles, but also the business environment, and often illustrate, which areas of action will receive specific support. With less frequency, strategies define overarching national goals (e.g. zero waste mining in India's strategy) and develop a kind of master plan for future actions under a common umbrella.

3.2.3 Transition strategy (block D 2 and F of the coding scheme)

Categories of measures: Across all clusters, measures from the realm of primary production, technological innovation, trade and environmental protection are mentioned most frequently. Only few strategies focus on measures targeting more sustainable consumption patterns, urban mining and product design, i.e. measures with a higher potential to drive fundamental change towards sustainability. Those that did, however, also expressed a need for transformation of resource patterns.

Means of intervention: Concerning the actual means of interventions chosen in the strategies, we did not identify any "intent"-type interventions, i.e. very deep leverage points. This corresponds with our findings on a lack of measures purposefully addressing a fundamental change of patterns of metal production and use. We found that strategies made frequent use of interventions from the system characteristics "parameter" (e.g. economic incentives, funding or technology transfer) – with low leverage – and "design" (e.g. information management, regulation or participatory measures) – with rather high leverage – , but rather neglected feedbacks (e.g. benchmarking and front-runner approaches, certification).

Interaction: Strategies most frequently referred to the supranational level. This holds true especially for European countries, which mention processes, initiatives, roadmaps and directives on EU level such as the EU Raw Materials Initiative(Commission of the European Communities (EC), 2008) or the Waste Framework Directive (European Parliament and Council, 2008). Links to the regional (sub-national) level address the role of provinces or federal states in supporting the implementation of measures suggested in the national strategy. Others express an intention to build up on and continue the work on transparency and CSR initiatives such as the Kimberley Process or the Canadian Whitehorse Mining Initiative (Fitzpatrick et al., 2011). Processes in other sectors (but on the same level) frequently touched upon in the strategies are planning and land use, research and research funding as well as biodiversity and conservation. Other links are made to preceding strategies such as a sustainable development strategy, poverty eradication strategy or to legislation that is linked to processes of resource production and use (e.g. a building code or policies of resettlement and rehabilitation).

Monitoring: Only few strategies suggest or plan to install a monitoring scheme for the actions suggested in the strategy, and only two countries state that they have already installed one. Usually strategies suggest an annual check and evaluation of performance, some plan to install intervals of 3 or 5 years. Six strategies express their intention to make use of indicators as part of the monitoring process.

4 Discussion

In general, strategies appear to be more detailed or more concrete when they include a section that explicitly depicts the initial situation, showing a direct link between the depiction of the current state and the actual transition strategy. Primary production is in the center of attention of measures and interventions suggested in the strategies. Only few measures can be considered to have a high change potential.

Largely different motivations drive the strategies in the four clusters of strategic documents we identified (see Table 1). Here, the initial situation and context – economically as well as geographical and political – have an influence on the strategy design, the preferred type of measures and the relation of actors such as the state and the private industry. This is specifically discussed by Ambe-Uva (2017) for African countries (clusters I and II). Similarly, Bartekova and Kemp (2016) identified distinct regional differences in criticality strategies, which they attribute to historically developed policy styles that are comparatively resistant to change. Such more in-depth studies of a selection of strategies and with a specific focus such as those of Bartekova and Kemp (Barteková and Kemp, 2016) or Hilpert and Mildner (2013) complement our findings. As an example, our analysis shows that many European countries make use of diplomacy and bilateral dialogue, but whether a strategy covers a certain category of measures does not tell us anything about its significance for the strategy as such. The study of Bartekova and Kemp (2016) tells us that policy dialogue is a distinct feature of the policy style of European countries, i.e., not one measure among many, but the pre-dominant one.

Our analysis shows that most strategies lack a clear theory of change. A coherent and "ideally evidence-supported" (Kay et al., 2014, p. 6) theory of change connects the current and target state through clearly depicting how change could occur. In doing so, it frames the whole strategy and forms the basis for the formulation of concrete action items that make up the transition strategy. However, strategies suggest single actions or, if they purposefully contribute to one specific goal, this is usually not reflecting a thorough understanding of more sustainable metal production and use. Two aspects in particular can and should inform strategy design in general, and such a theory of change for the design of strategies in particular: (i) in terms of content, a clear orientation towards and operationalization of sustainability principles as the over-arching goal (see 4.1), and (ii) in terms of process, a sufficiently comprehensive, flexible and resilient strategy design targeted towards continuous improvement and informed by a diverse understanding of time (see 4.2).

4.1 Content-related factors: the role of sustainability for driving (fundamental) change

Regarding the content of strategies, we found three aspects to be of specific relevance: The actual integration of sustainability principles that should go beyond mentioning the term (4.1.1); the over-arching goal targeted by strategies (4.1.2); and the choice of measures and means of intervention that may influence the possible contribution to achieving a more sustainable metal production and use (4.1.3).

4.1.1 Integrating sustainability as a concept: Beyond 'mentioning' sustainability

Sustainability is not the motor or motivation for most of the strategies, and thus sustainable resource use is not in the focus or approached systematically in the majority of strategy documents. Rather, they often direct the suggested measures towards sustaining resource availability or operating sustainably. They rarely include other aspects like justice, participation or distribution, or aiming towards sustainable development through resource production and use. The predominant "coping strategies" focus on national interests such as attracting investment or securing supply through conventional, mostly economic means, and seem to aim towards fostering the status quo rather than achieving actual change. To support a sustainability understanding that can easily be operationalized in a set of actions, it is important to be aware of and differentiate the somewhat two-fold relationship of resource use and sustainability: 'achieving sustainable resource use' on the one hand and 'developing the role of resources for achieving sustainability' on the other.

Even though several suggestions and approaches elaborate on sustainable ways to make use of (scarce or non-renewable) resources (Bringezu, 2015; Henckens et al., 2014; Moran and Kunz, 2014; Norgate and Rankin, 2002; Prior et al., 2012; Tilton, 1996; Wäger et al., 2012), there is no broadly accepted definition of what sustainable resource use might entail. However, many studies, reports and guidelines can serve as a point of reference for defining the sustainability rationale employed throughout a strategy that aims to foster sustainability in metal production and use. As internationally agreed goals, the SDGs may serve as guidance for defining the desired target state as well as the design of comprehensive and integrative strategy action to fill the gaps we found in this regard and make a positive contribution to achieving the SDGs. In this context, it is important to consider the SDGs as interlinked goals, in which strategic approaches can either benefit or hinder a joint implementation, rather than using them as a 'checklist' for issues that need mentioning (Lewis and Flynn, 2016; Nilsson et al., 2016).

4.1.2: Differentiating measures from the overall goal: From standards to absolute reduction

The International Resource Panel (IRP) emphasizes that decision-makers need to prioritize actions based on a profound understanding of the interrelations and impacts of resource-related actions, and that they need to cooperate with industry to work out strategies for decoupling resource use from negative social and environmental effects and to stimulate innovation for increases in resource efficiency (United Nations Environment Programme (UNEP), 2012). International standards for reporting and certification can provide orientation for more specific aspects of the life cycle, especially those associated with mining, e.g. the Global Reporting Initiative or environmental management standards. Technological innovation, improved exploration and more efficient production processes may further contribute to minimizing negative impacts of metal production and use. The aim of such innovation, however, should be an overall absolute reduction of exploitation of resources. But while some countries have generally acknowledged the necessity to avoid over-exploitation, quantitative targets for absolute decoupling are rarely in place (Bringezu et al., 2016). This stands in deep contrast to an ever-increasing demand, especially for resources used in modern energy and mobility technologies (Elshkaki et al., 2016; Moss et al., 2013; Vidal et al., 2013; Watari et al., 2018). As of today, efficiency improvements only show limited effects. Most countries have achieved no or only relative rather than absolute decoupling of economic growth and resource consumption, and resource-intensive industries are often just being outsourced to other countries (Giljum et al., 2014). These aspects – as well as total substance, materials and product flows – are very much underrepresented in the strategies we analyzed, but should be an integral part of future strategies targeting sustainable resource use.

4.1.3: Measuring progress and assessing the potential for change

Meadows (1999) strongly emphasizes the role of paradigms for shaping other points of intervention such as goals and information flows. While rather shallow leverage points such as subsidies and taxes can "create beneficial outcomes" (Abson et al., 2017, p. 33), we argue that in order to bring about transformative change towards sustainable metal use, strategies ought to make use of deep leverage points, which target the overall intent and mindset of a system. This connects to our findings on the measures and means of intervention suggested in the strategies. Even though strategies in our sample made use of some rather deep leverage points like governance measures, this does not tell us anything about the direction and transformative potential of the suggested interventions towards achieving more sustainable metal use. Our analysis of categories of measures indicated that governance measures were not generally set up to drive such fundamental change. That means that as long as strategy actions are not guided by the need and objective of achieving "paradigm change" towards sustainability, and direct all suggested interventions towards this goal, they will not achieve the needed change, independent of the actions they suggest and the points of intervention they choose.

Here, the framework by Moran and Kunz (Moran and Kunz, 2014) to assess sustainability progress and performance is helpful. In applying their criteria of measuring progress to our analysis, we found that most strategies are in stage 2 or 3 of the maturity scale, focusing on efficiency in their operations or working towards effectiveness through an integrative perspective on system components. Some of the approaches grouped in clusters III (Our resources for our industry) and IV (Closing cycles, securing supply) that have started to take on a life-cycle perspective more explicitly (such as Finland, Denmark and Germany) can be assigned to stage 3. They are increasingly valuing networks and connectivity in information flows to achieve fruitful exchange along decision-making pathways from local to higher levels, but also among entities on the same regulatory level. Again, however, at its core this is often not necessarily driven by achieving sustainability, but rather by securing supply. Which equity condition is mainly considered in strategies corresponds, at least to some extent, with the clusters of countries we identified in our analysis. Countries from cluster IV, which are usually highly dependent on importing metals for their industries, aim for "demand met at reasonable prices" (condition 2), while the more resource-rich countries in groups I, II and III rather aim for supplier prosperity (condition 1). Strategies rarely refer to meeting future needs (condition 3) in the context of equity and sustainable development.

While the stages of maturity allow us to assess the status of operations on the path towards sustainability, the concept of leverage points could help us define the necessary actions or target areas of actions to enable such a transition in each stage. As an example, rather shallow leverage points like taxes and subsidies (= parameters) may contribute to increased efficiency (stage 2) and may also support a move towards effectiveness (stage 3), e.g. through setting regulative standards for closer cooperation and networking (integrating by connecting). Especially with regards to dissipation, this is insufficient for fostering sustainability along the metals' life cycle (Kümmerer, 2016), but could deliver intermediate solution on the path towards this goal. Reaching the stage of adaptability and resilience (stage 4) demands a profound understanding of the larger system, its actors and the values that drive and underlie all actions, so measures would have to target the design and intent of the system (deep leverage points). Many studies emphasize the importance of education, research and increasing our knowledge on the cycles of elements in anthropogenic systems (Chen and Graedel, 2012; Meinert et al., 2016), but – as noted before - still only few of them make a connection to consumption patterns. This calls for more interdisciplinary approaches, which link the existing body of literature on consumption and behavior to that on resource production, and transfer this knowledge into resource strategies (Dominish et al., 2018).

Closely linking sustainable development to a variety of equity conditions also reflects the normative dimension of achieving sustainability in resource use that we also found to be largely unaccounted for in existing strategies. The differentiation of four different kinds of equity holders may inform future strategy making also regarding the multiple dimensions of the desired target state and necessary interlinkages with other processes or regulative levels. The increasingly integrative perspective when moving towards operating sustainably is asking for (coordinated) cooperation of a variety of actors from very different domains (Bringezu et al., 2016).

4.2 Procedural factors: Focus, scope, and monitoring

Regarding procedural factors of the strategies, we found three aspects to be of specific relevance: A strategy's focus should go beyond issues of metal availability (4.2.1); strategies need to balance comprehensiveness and concreteness (4.2.2); monitoring may support continuous improvement (4.2.3).

4.2.1 Aiming to focus beyond availability issues

Across the sample, the clear focus on the economic aspects of resource use as well as on the first stages of the value chain reflects the concerns about resource availability for technological innovation and future prosperity that predominantly define the (scientific) discourse on metal supply and demand (Angerer, 2010; Dewulf et al., 2016; Erdmann and Graedel, 2011; Graedel et al., 2015b; Mason et al., 2011b). In this context, many studies emphasize that processes within the value chain must be considered in a broader and more comprehensive context (Giurco et al., 2006; Stewart et al., 2006). However, circular economy approaches, as suggested by some (Commission of the European Communities (EC), 2015), still face some feasibility challenges. Technological innovation in recycling cannot fully inhibit dissipation, especially for devices with only small fractions of metals combined in one appliance such as in smartphones (Dießenbacher and Reller, 2016; Kümmerer, 2016; Weiser et al., 2017a). With regards to specific metals, the contribution of end-of-life materials could continue to be negligible for several decades to come in comparison to primary production, as suggested by Werner et al. (2018) for the case of indium in Australia. Strategies should therefore not only aim for closing the loop in the recycling phase, but should also incorporate product longevity and options for remanufacturing and reuse (Dominish et al., 2018). This link to product design, distribution and use as well as behavior issues has a high potential to drive change, but is rarely made in the strategies we analyzed.

4.2.2 Balancing the strategies' scope between comprehensive and concrete

In the attempt to take a holistic approach, Kunz et al. (2013) warn not to fall for the "Holism Panacea", i.e. formulating too general actions. Issuers should decide, which level of concreteness and comprehensiveness should be applied for the specific strategy and apply this focus to all parts of the strategy. They should clearly state the strategy's aim and focus and make distinct links to those areas of action that are impacted by changes in the realm of the strategy (including a clear reference to other strategies and sectors like waste management and sustainable consumption), but not necessarily attempt to cover all aspects of the system at hand. This reflects the need for systems-oriented models underlying the description of the current and target state (Kay et al., 2014). Strategies should thus include an interlinked, systems-based description of the current state and – on a corresponding level – a complex vision and a sufficiently differentiated and complex transition strategy that links the current and the targeted future state. Depending on the operational level of the strategy and the focus it has, the system boundaries can be drawn either rather broad or narrower. Different strategic actions and interventions may be suitable for different resources, as suggested by Henckens et al. (2019). A reasonably focused, more systems-based approach would then also help to determine the most relevant challenges a strategy ought to tackle.

4.2.3 Using a monitoring mechanism to work towards step-wise, but continuous improvement

Achieving sustainable resource use, especially for non-renewable resources like metals, asks for ambitious steps to be taken in a coherent and timely manner and will not be achieved within a few years. Actors should consider this by issuing strategies that can work as tools for a continuous, but dynamic improvement process. Strategies should include (i) a defined sequence of actions that build up on or complement each other and leave room for adapting to changing environments, (ii) clearly stated addressees of the tasks involved, and (iii) the installation of concise monitoring mechanisms to regularly revisit and adapt the strategy to on-going developments.

"Sequence" in this respect also has a variety of temporal connotations that go beyond a linear understanding of time in the sense of, e.g. the period of years it covers. Sustainability as a guiding principle also means to aim for flexibility and adaptability to allow for quick reactions to changes, which might occur during the strategy's lifespan (Weiser et al., 2017a). Monitoring progress calls for smart reasoning not only concerning the use of indicators, but also with regards to monitoring intervals. Concerning the strategies' time-frame, and based on the strategies in the sample we analyzed, it must be noted that "long-term" is not enough, if it means that there are no clear targets or concrete suggestions for actions to be taken in the more distant future or no clear statements of what the strategy contributes to achieving long-term goals.

Monitoring and reflexivity are also the fourth vital part of Loorbach's transition management cycle (Loorbach, 2010) (described in 2.1). Many approaches such as the 'social license to operate' as well as suggestions for indicators to monitor and assess resource-related actions especially in primary production and trade exist (Corder et al., 2010; Falck and Spangenberg, 2014; ICMM, 2006), but may still lack a connection to later stages to offer a more integrative, connected approach to learn and improve. This includes learning through interaction with others, which was discussed in some of the strategies, e.g. in order to profit from the EU's experiences with their Raw Materials Initiative (Commission of the European Communities (EC), 2010). Furthermore, Moran and Kunz (2014) note that in order to achieve the stage of adaptability and resilience, knowledge would have to be co-produced by actors from science and practice. So far, comparatively few countries have chosen to formulate a strategy document and make it publicly available (ideally in English language), which would be a first step to enable exchange and mutual learning across countries. Additionally, only few strategies showed evidence of an intense stakeholder dialogue or strategy co-design with actors from across science and practice. Ideally, a transition strategy is based on not only a differentiated, but also shared vision that can be understood by all relevant stakeholders (Kay et al., 2014; Wiek and Iwaniec, 2013). Once more, this puts emphasis on the role of actors, as the strategies' addressees, but also as their co-designers. Examples for such visioning processes connected to resource strategy making are discussed by Lederwasch et al. (2011) and Mason et al. (2011a). The quality criteria for sustainability visions developed by Wiek and Iwaniec (2013) may serve as guidance for designing the vision in a way that guides actual transition towards sustainable resource use.

4.3 Recommendations for future strategy design

Our analysis revealed that existing strategies lack a comprehensive approach towards fostering sustainability along the metals' life cycle. Available strategies have the potential to guide policies and especially to connect and embed resource-related activities in a broader context, but still need improvement to guide actual change towards sustainable resource use.

Table 2 sums up the discussion of our findings by stating recommendations for the design of strategies that target more sustainable metal production and use. The table differentiates general recommendations (first row) from those that are specifically relevant for single clusters of approaches and follows the structure of our conceptual framework that we also applied to present our findings.

Table 2: Recommendations for future resource strategies (in general and for each cluster type) ordered by the categories of our theoretical framework (see ch. 2.1)

	Overall Strategy Design	Current state	Target state	Transition strategy	Theory of change
General	- clear addressee(s) - involve stakeholders in the strategy design process whenever possible - design strategy in relation to other levels and processes - clearly state focus and aim	- decide on reasonable time frame, differentiating short-, mid- and long-term future goals as well as historic developments - clearly describe initial situation and motivation to issue strategy	- state a clear and shared vision to provide orientation for long-term goals - aim for overall transformation of resource production and use - define sustainability and make it an explicit component of strategy design	- set up monitoring mechanism and use indicators (comparison) - use scenarios to formulate short- and mid-term actions that refer to the vision - consider all possible drivers of unsustainable resource use - aim for flexible, resilient structures	- incorporate change management principles (e.g. transition - management cycle) - aim for increasing use of deep leverage points to achieve paradigm changes - make use of SDGs as point of reference to follow a

I_Upscaling Exploration	- embed strategy within its geographic and political context and make active use of connections to other processes instead of just mentioning their existence - use maturity stages and equity conditions (Moran and Kunz 2014) as points of reference to assess current situation and formulate targets	- focus on primary production, but make links to later life-cycle phases - consider long-term trends in demand as well as exploration processes in other regions	- employ a sustainability understanding that goes beyond "sustained resources" - - make sure increased exploration is not happening at the expense of others (consider equity holders)	- aim to consolidate exploration targets with (indigenous) land use rights, e.g. through participation in the strategy design process	comprehensive approach
II_Mining for Development		- focus on primary production, but make links to later life-cycle phases and to other areas of action affected by mining	- aim to move from maturity stage 2 to 3 - build a governance scheme that provides stability, but allows flexible reaction to changes	- foster technological innovation, with clear links to other life-cycle phases	
III_ Our resources for our future		- cover whole life-cycle with a focus on later stages - include issues like health and safety	- consider need for absolute reduction - make use of deep leverage points to get to stage 4 of the maturity scale	- especially consider behavioral and informational drivers of unsustainable resource use - - put more emphasis on product design and consumer behavior	
IV_Closing cycles, securing supply		- focus on design, use and secondary production, but consider commodities' origin (responsible sourcing)	- develop a clear idea of *how* to transform metal use (think of resources and resource use also as contributing to SD) - consider need for absolute reduction	- responsible sourcing - especially consider behavioral and informational drivers of unsustainable resource use	

Concerning the development of an over-arching (multi-scale) resource governance scheme, more research is needed to define, which type of action and regulation is needed at what level. We agree that many of the questions related to sustainable metal use must be answered internationally. This holds true especially for questions of justice like a fair distribution of the environmental burden associated with metal production and use and the conservation of natural resources. We postulate, however, that these ideas must not only be guided by a shared and comprehensive vision and transition strategy to facilitate actual change towards sustainable resource use. Rather, they should embrace diversity and context and be closely linked to action on national and regional scale in consideration of their specific needs, objectives and the challenges they face.

Our selection of variables differentiated the current and target state and the actual transition strategy. Together with a special focus on sustainability and temporal aspects, this proved to be useful to derive implications as to what and how to compare strategies albeit their diversity and could be used similarly for the analysis of other strategy documents and from different sectors. This would enhance the possibilities for actors to learn from each other, and allow a transfer or scaling and adaptation of good practices.

APPENDICES

Annex 1: Detailed description of methods

The following overview shows in detail the approach we followed in our analysis, especially step 2: coding and analyzing.

Table A 1: Overview of approach to document analysis

Step of Analysis	Action & remarks	Result
1. Definition of selection criteria	criteria - policy document (strategy, plan, program, initiative - *compare strategy definition (section 1)*) - relate to (mineral) resources, mining, resource security, ... - English language - original/ primary sources (no reports on specific policies, strategies, ...) - available to the public	search string: (policy OR policies OR initiative OR strategy OR plan OR program) AND ("raw material" OR "mineral" OR "critical metal" OR "critical material" OR "resource" OR "mining") AND [COUNTRY NAME] -"human resource"
2. Data gathering	1. Google advanced search (conducted Dec. 2017) plus a non-country specific repeated search process without (policy OR policies) and (mining), to also find what is not a mining/ mineral policy (Apr. 2018) 2. direct search for documents mentioned in secondary literature and on the website of the Horizon 2020 MIN-guide project: (search criteria: country: all; policy instrument type: policy strategy; value chain relevance: all phases; policy type: any) 3. snowball search starting from the following reports: - defra 2012(defra, 2012) - Hilpert and Mildner (Hilpert and Mildner, 2013) - MIN-guide project minerals policy country profiles (EU member states)	Search resulted in a set of 84 documents.
3. Data screening, cleaning and scoping	excluding: - legislation, reports, general development plans and strategies (i.e. not explicitly focusing on resource-related aspects) - documents dealing with non-mineral resources only (water, forest, ...) - specific criteria for the case of several documents from the same country applied*	32 documents did not meet the selection criteria upon closer screening. Final set transferred to review data table.
4. Full-text analysis	Coding scheme based on analytical framework (see section 2). List of categories for analysis transferred to review table and used for analysis of selected strategy documents. Criteria as defined through pre-study research consisted of 6 general blocks for analysis informing the current and target state and the transition strategy	Eventually focusing on national level only, so 15 documents from the regional or inter-/ multinational level were deleted from the set; final sample consisted of a set with N = 37 documents.
5. (Statistical) Analysis	- Evaluation of coded data in review data table using MS Excel for analyzing count data and R for an exploratory cluster analysis and multiple correspondence analysis (MCA). - For the R analysis, the variables "monitoring" and "interaction" were excluded. The entries for these	Dendrogram allowing to cut into 5 clusters Multiple correspondence bi-plot showing the two main gradients between strategies

variables included many NA values and mixed factor levels for many individual entries. Therefore, they were considered a different type of variable than most of the other variables, which were largely binary variables. Since this study aimed at identifying large scale patterns it was deemed acceptable to exclude these variables, without compromising the goal of analyzing a comprehensive set.

- The cluster analysis was applied on the variables of the review data table that represented a binary coding. Using base R methods, Ward`s hierarchical agglomerative clustering algorithm(Murtagh and Legendre, 2014) was applied on the distance matrix that was calculated using the (asymmetric) binary distance metric.
- Using the FactoMineR package, we applied a multiple correspondence analysis on the same data set of binary variables and used the factoextra package for analyzing results and plotting. (Husson et al., 2010; Kassambara and Mundt, 2017; Lê et al., 2008)
- For the biplot of the MCA we first inspected all variables and, in a second step, limited the analysis to the 45 variables with the highest contributions. In addition, we added the variables "sust.rat.reso_1", "sust.rat.contrsd_1", "sust.rat.opera_1" to the plot, since these helped understanding the general meaning of the gradients knowing that their contributions are rather low.

It must be noted that our sample is limited to the national level and included only documents that were publicly available, so the results are not representative for all strategies (some or most of which might be either unpublished or even unwritten). A country or region not listed does not provide absolute security on whether a state does or does not have a strategy at all. It rather shows that such a document could not be found by the means employed. Furthermore, the analysis of strategy documents does not provide any insights on the overall governance of metals and resource use. Our results rather provide an overview of what strategies cover without further evaluation of those findings. The criteria in each block do not aim to be comprehensive, but rather represent the actual content of the strategy documents to allow for their comparison: The block on sustainability cannot replace a comprehensive sustainability assessment.

** Selection: if data gathering resulted in several documents from the same issuer, the document that was as broad as possible with regards to life cycle phases, but as specific as possible with regards to raw materials in the focus, and/ or the most recent one, was analyzed and others noted down as existent in the special remarks section.*

Annex 2: Background information on conceptual framework

We describe here, where the categories and variables originate and, if applicable, show the connection to temporal issues and sustainability.

The current state

We analyzed the context, in which the strategy was developed, and collected information about the **economic situation and role of resources** for the national economy (Ali et al., 2017; Behrens et al., 2007; Wellmer and Wagner, 2006), the overall scope of the strategy and challenges and motivation. Since we focused on national strategy documents, the spatial scope was pre-defined for most documents. Questions regarding the aspects of time and sustainability, however, arise – among other – concerning the **temporal extension of a strategy** (both into the past and future), the objective of securing long-term availability of a finite resource or in dealing with the global dispersion and unequal distribution of metal ores (Mason et al., 2011). Scope also involves the **life-cycle phases** covered by a strategy (Chen and Graedel, 2012; Jackson et al., 2014; Wäger et al., 2012). Whether and how the current situation is described can tell us a lot about what motivated strategy issuance. There is a strong connection to **temporal aspects** in sustainability actions, either in the sense of "time rhetoric" (e.g. in the perception of urgency) or concerning the need for a long-term perspective, strategies as response to acute changes or as part of a continuous process (Kümmerer, 1996; Weiser et al., 2017). **Challenges** stated in literature (Bleischwitz and Bringezu, 2008; Habib and Wenzel, 2016; M. L. C. M. L. C. M. Henckens et al., 2014; Moran and Kunz, 2014; Petrie, 2007; Van Schaik and Reuter, 2004; Wäger et al., 2012) focus on geological issues (depletion, scarcity) or on criticality and its causes, which can be economical, political, technological, social or environmental (Graedel et al., 2012; Wäger and Lang, 2010).

The target state

To draw from the strategy documents what is considered as a desired target state, we analyzed the visions, objectives and further statements made about the targeted future state as well as the role of sustainability in that. Sustainability is rarely in the focus of attention in the analysis of resource strategies. Whether a strategy aims to achieve **sustainability** at all is thus important to ask initially. Since there is no coherent understanding of what sustainable resource use could entail in literature, we applied three **rationales to categorize the role of sustainability** in each of the documents:

- *"Sustained resources":* addresses sustainability in the sense of "mineral resource sustainability" (compare e.g. (Mudd, 2007)) and/ or sustaining (economic) development
- *"Operating sustainably":* addresses sustainability in the sense of "environmental costs or resource intensity" of resource extraction and use throughout the whole life-cycle
- *"Contribution to Sustainable Development":* addresses sustainability in the sense of resource use contributing to sustainable development (including e.g. equity, well-being, ...))

Hirschnitz-Garbers et al. (2016) define four sets of **drivers for unsustainable resource use** that strategies would need to tackle in order to address "transformation" of resource use patterns towards more sustainability, which are further explained in the coding scheme in Annex 2: (i) behavioural and informational, (ii) policy and regulatory, (iii) socio-economic and (iv) technological and infrastructural.

Defining a target state and thus engaging with the future has a strong temporal connection, too. It links to policy styles that are distinctive for specific countries or groups of countries and often reflect historical developments, in which strategies can and must be seen (Barteková and Kemp, 2016). We therefore differentiated, for example, whether the strategy is rather reactive and **describes on-going developments**, to which it aimed to adapt, or rather actively **envisions a distinctly different target state** it aims to reach.

The transition strategy

The development of concrete strategic actions can be based on a broad array of **potential approaches** for future resource use (Behrens et al., 2007; Bringezu, 2015; Christmann et al., 2007; M. L. C. M. L. C. M. Henckens et al., 2014; Moran et al., 2014; Wäger et al., 2012). Increasingly, it is acknowledged that such approaches should cover the whole value chain and be subject of a superordinate resource governance scheme (Ali et al., 2017; Bleischwitz and Bringezu, 2008; Wäger et al., 2012; A. Weiser et al., 2015). To draw from our analysis information about the actual transition strategy suggested, we differentiated (i) in which fields of action the strategies aimed to intervene (**categories of measures** including i.a. product design, technological innovation) and (ii) which **means of intervention** they chose (e.g. incentives, legislation, diplomacy).

We also analyzed which of the topics that the sustainability agenda of the **Sustainable Development Goals** (SDGs) (United Nations, 2015) addresses were covered by the strategies (such as poverty reduction, clean water and sanitation). This had implications both for the sustainability understanding employed in the strategy and for how **comprehensively** strategies approached future challenges.

Besides analyzing which actions the strategies suggested to take, we also considered *how* they intended to reach the desired target state. (i) Suggested **measures can drive different kinds of change**, from keeping or improving the status quo to a completely new way of thinking and acting. Measures aimed at closing the loop, changing product design towards recyclability and tackling absolute consumption may have higher potential to drive change than measures sustaining or improving the investment climate. The overall **means of intervention** we analyzed can thus be categorized as rather **shallow or deep leverage points** according to the system characteristics suggested by Abson et al. (2017): *Parameters and feedbacks*, which represent more shallow leverage points, and *design and intent*, which include the deeper leverage points and are considered by Meadows (1999) to be more effective to bring about system changes.

Defining a transition strategy as a **sequence of transition actions** hints at its temporal dimension. Besides the overall time-frame of the strategy, it could aim for incremental changes, where single actions are building up on each other (Feola, 2015), or suggest single actions that are not linked to each other and disregard the **system-inherent temporalities** of each intervention (Weiser et al., 2017). In that respect, strategies can be used as a management tool for **continuous improvement**, where targets are set and regularly revisited to adapt to recent developments (Loorbach, 2010). **Monitoring mechanisms** would thus be an important component of a resource transition strategy (Bringezu et al., 2016; European Commission and Eurostat, 2015).

Annex 3: Full coding scheme

The coding scheme for analyzing the strategy documents consisted of six blocks with a variety of criteria for each, three relating to context and three to content. The coding process was partly an iterative process, i.e. we formulated additional categories of the coding scheme based on the first results of the analysis. These additional coding categories are marked in grey.

Table A 2: Full coding scheme

Block	Information	Source or reference (if applicable)	Operationalization and/ or coding
Basic information	issuer data		document title [name]
			sub-title
			country/ region [name]
			issuer [name]
			[regional - national - multi-/ inter-national]
	year		year of issuance [YEAR]
	pages		[total amount]
Sampling	found through:		search string (google) [0/1]
			hint in secondary literature [0/1]
Special remarks			
Block A: Economic situation	Economic data	*(World Bank data, rounded to 1 decimal and given for reference year 2014 if not otherwise stated)*	class (LMI = low or middle income; HI = high income)
			GDP per capita (current USD)
			Total natural resources rents (% of GDP)
			Mineral rents (% of GDP)
			Ores and metals exports (% of merchandise exports)
			Ores and metals imports (% of merchandise imports)
			remarks on data sources
		(CIA World Factbook, accessed 21/01/2018)	main natural resources
	country group	*Based on cluster analysis and MCA*	*I - IV*
Block B: Scope and overall approach	organizational/ approach		strategy formulation process involved participation, stakeholder dialogue, consultation, and/ or a transdisciplinary approach (1/0)
			details/ remarks
	temporal		time frame (total) [years from issuance to last target year mentioned]
			time horizon [last year of strategy horizon]

Block	Information	Source or reference (if applicable)	Operationalization and/ or coding
			argumentation is backed mainly by information and data from the past or by forecasts and potential future states [past - current - future - balanced]
			if temporal scope as such is not defined, which is the most distant future date mentioned ?
			notes and comments
	Resource groups	*i.a. adapted from* (Bundesministerium für Umwelt Naturschutz und Reaktorsicherheit (BMU), 2012)	degree of specificity
			raw materials / groups covered [only if there is a specific focus!]
	life cycle phases covered throughout the strategy [0/1]	*adapted from* (Hagelüken and Meskers, 2010; van Berkel, 2007)	exploration & primary production
			transport and trade of commodities
			Product design & manufacture
			Product use
			End-of-life & secondary production
			strategy also covers interlinkages between life cycle phases
	Which of the issues covered through the Sustainable Development Goals does the document mention (without referring to them explicitly and without necessarily mentioning them as goals of the strategy etc.)? [0/1]	(United Nations, 2015)	1 - No poverty
			2 - Zero hunger
			3 Good health and well-being
			4 - Quality education
			5 - Gender equality
			6 - Clean water and sanitation
			7 - Affordable and clean energy
			8 - Decent work add economic growth
			9 - Industry, innovation and infrastructure
			10 - Reduced inequalities
			11 - Sustainable cities and communities
			12 - Responsible consumption and production
			13 - Climate action
			14 - Life below water
			15 - Life on land
			16 - Peace, justice and strong institutions
			17 - Partnerships for the goals

Block	Information	Source or reference (if applicable)	Operationalization and/ or coding
Block C: Initial situation, challenges and motivation	PERSPECTIVE		Strategy document has a section that explicitly describes the initial situation to which the strategy aims to respond [0/1]
	depiction of initial / current situation and consequent argumentation are backed by… [0/1]	*on-going reiteration from strategy analysis*	economic and scientific data (statistics, estimated, stocks and flows, …), research and analysis
			historical information and long-term developments (going back 15 yrs or more)
			description of recent (geo-) political events and/or recent trends and changes that need reaction (last 5 to 10 yrs or less)
			details/ remarks // OTHER
	(long-term) change and urgency [0/1]	*(see* (Petrie, 2007)*: "fundamental need for re-orientation of the minerals and metals value chain")*	strategy document expresses a need for transformation/ transition of resource use patterns (in general)
			strategy document expresses a need for adaptation or change responding to on-going developments (i.e. focus is on change within the scope of the strategy's issuer)
			strategy document expresses some degree of urgency to act
			strategy document expresses the need for a long-term perspective on transformation and sustainability and/or resource supply
	motivation [0/1]		*Seizing opportunities 1: New markets and technologies* (New markets and technologies as an opportunity to make better use of the potentials of the resource industry for the national economy.)
			*Seizing opportunities 2: Demand fueling local mining industry (*Increasing demand as an opportunity for the (mining) industry, where motivation focuses on improving the investment climate.)
			*Seizing opportunities 3: Governance and stability (*A political situation that demands and allows re-orientation of governance structures and capabilities or revisiting the roles and relationship of the state and private industry.)
			Averting negative effects 1: Progress for competitiveness (The recognition that change must come in terms of (technological) innovation in order to meet environmental and social standards and to become or remain competitive.)
			*Averting negative effects 2: Preparing for disruptions (*The recognition that global market developments, especially increasing demand, ask for some kind of action to be taken, and where a need is seen to either "close the loop" or to diversify supply structures in order to avoid or buffer the effects of market disruptions.)
	PERSPECTIVE		strategy document explicitly refers to specific challenges it aims to address
	challenges mentioned (incl. implicit, i.e. when strategy text depicts an	(Bleischwitz and Bringezu,	supply risks or restricted access *(resource criticality, rising demand, market disturbances or distortions)*

Block	Information	Source or reference (if applicable)	Operationalization and/ or coding
	awareness for the following challenges associated with resource use) [0/1]	2008; Habib and Wenzel, 2016; M. L. C. M. Henckens et al., 2014; Moran and Kunz, 2014; Mudd et al., 2014; Petrie, 2007; Scholz and Wellmer, 2013; Wäger et al., 2012)	resource depletion (geological; incl. more difficult extraction etc.)
			adverse effects of resource production and consumption *(social, environmental)*
			(import or export) dependence
			technological *(mining, recycling, ...)*
			competition (global), investment climate (incl high degree of regulation)
			other challenges named
Block D: Objectives and measures	PERSPECTIVE: How does the strategy document engage with "the future"? [0/1]	(Shipley, 2002; Wiek and Iwaniec, 2013)	Describes probable future developments and estimates, to which the strategy's measures are meant to help to adapt
			Describes or envisions a desirable future state and develops new ideas for the field
			if applicable: quote, if a vision is explicitly stated:
	objectives		QUOTE (relevant text passage/ page)
	strategy covers measures from the following categories: [0/1] (technological and economic approaches for single life cycle phases, substitution and urban mining, processes linked to the value chain)	(Behrens et al., 2005; Bleischwitz and Bringezu, 2008; Christmann et al., 2007; M. L. C. M. Henckens et al., 2014; Moran and Kunz, 2014; Wäger et al., 2012)	prospecting and exploration incl. geological mapping and mineral surveys
			mining
			product design
			EoL treatment and waste management
			circular economy, closing the loop & recycling
			investment climate
			resource/ material efficiency
			energy efficiency
			trade and competition
			supply security, diversification
			technological innovation
			substitution
			urban mining
			health and safety (mining, workers)
			consumption patterns, total material consumption
			conservation, environmental protection and mine site reclamation practices
			land use

Block	Information	Source or reference (if applicable)	Operationalization and/ or coding
			other (name) (otherwise: ND)
	cornerstones		the strategy's cornerstones: suggested steps, actions and targets [name]
			notes and comments (esp. on role of state/ issuing organization)
	overall means of intervention [0/1]	(Wäger et al., 2012; Annika Weiser et al., 2015)	economic incentives & fiscal regime (tax reductions, repayable loans,...)
			funding or financial support (research programs, ...)
			governance: legislative acts and regulation, policy- and decision-making
			active engagament with/ in exploration, mining, trade and affiliated processes
			benchmarking and best practice-based improvement principles
			information management, knowledge sharing, education, training and communication; R&D
			participation & involvement
			business practice/ CSR + reporting, certification
			development aid and technology transfer
			diplomacy and bilateral dialogue; collaboration and networking
			notes and comments (otherwise 0)
	concreteness of measures [0/1]		strategy suggests concrete actions, even if they still need further operationali-zation and concretion
			notes, comments, examples (if applicable: exemptions) (otherwise: 0)
	monitoring [0/1]	(Bleischwitz and Bringezu, 2008; Massari and Ruberti, 2013; May et al., 2012)	monitoring mechanism? [none (or not defined) - suggested - planned - installed]
			if yes: monitoring intervals (in years)
			if yes: use of indicators?
			notes and comments
Block E: Sustainability	Overall framing and understanding ("rationale")		sustainability mentioned as a term (sustainab*)
			definition for sustainability offered
			quote
		(Figge et al., 2014; M. L. C. M. Henckens et al., 2014; Moran et al., 2014; Moran and Kunz, 2014;	**"Sustained resources":** addresses sustainability in the sense of "mineral resource sustainability" (compare e.g. Mudd 2007) and/ or sustainable (economic) development
			"Operating sustainably": addresses sustainability in the sense of "environmental costs or resource intensity" of resource extraction and use/ throughout the whole life cycle

Block	Information	Source or reference (if applicable)	Operationalization and/ or coding
		Mudd, 2007; Norgate and Rankin, 2002; Wäger et al., 2012)	**"Contribution to SD":** addresses sustainability in the sense of resource use contributing to a more sustainable development (SD, equity))
	strategy addresses the following drivers of unsustainable resource use (in the context of sustainability)	(Hirschnitz-Garbers et al., 2016)	Behavioural and informational *(Consumption and production patterns; Knowledge/ information; Paradigms, world views, perceptions, aspirations)*
			Policy and regulatory *(Legal-administrative settings and political actions)*
			Socio-economic *(Investments/ financial & human resources; Resources prices; Socio-economic conditions; Trade patterns/ global markets)*
			Technological and infrastructural *(Complexity, vulnerability and applicability of technologies and production processes; Infrastructure/ technology design/ use)*
	strategy addresses aspects of … (in the context of sustainability)	(Caron et al., 2016)	justice and equity
			distribution
			well-being
			resilience, precaution or adaptation
			CSR// Business ethics and transparency
			participation and inclusion
			other (name)
			Note
Block F: Interaction	strategy document refers to processes in the same field, but on other regulatory levels		[1/0]
			processes on BUSINESS level: 1 = refers to past processes it builds up on or continues OR 2 = calls for future action to be taken that intervene with strategy 3 = mentions milestones in interaction with/ parallel to own strategy process
			namely
			processes on REGIONAL level: 1 = refers to past processes it builds up on or continues OR 2 = calls for future action to be taken that intervene with strategy 3 = mentions milestones in interaction with/ parallel to own strategy process
			namely
			processes on NATIONAL level: 1 = refers to past processes it builds up on or continues OR 2 = calls for future action to be taken that intervenes with strategy

Block	Information	Source or reference (if applicable)	Operationalization and/ or coding
			3 = mentions milestones in interaction with/ parallel to own strategy process
			namely
			processes on SUPRANATIONAL level: 1 = refers to past processes it builds up on or continues OR 2 = calls for future action to be taken that intervenes with strategy 3 = mentions milestones in interaction with/ parallel to own strategy process
			namely
	strategy document refers to processes on the same level, but in other areas or fields of action	(Bleischwitz and Bringezu, 2008; Giurco et al., 2014)	[1/0]
			sustainability
			biodiiversity and conservation
			planning and land use
			product cycles, waste and recycling
			research and research funding
			development aid and policy
			production processes, efficiency
			product design
			OTHER
			namely
	strategy document refers to earlier processes in the same field (usually on the same level, or on others but where the issuer was involved)		[1/0]
			namely

Annex 4: List of countries, documents and clusters

Table A 3: List of countries, document title and cluster they belong to

COUNTRY	DOCUMENT TITLE	CLUSTER	
Austria	The Austrian Minerals Strategy	0	(outliers)
Austria	The Austrian Mineral Resources Plan	0	
Japan	Strategy for Ensuring Stable Supplies of Rare Metals	0	
Afghanistan	Rare Earth Elements and Metals Policy	I	**Upscaling Exploration (9 documents)**
China	China's Policy on Mineral Resources	I	
Mongolia	State Minerals Policy 2014-2025	I	
Somalia	Somali Maritime Resource and Security Strategy	I	
Vietnam	Mineral Resources Strategy to 2020 with a vision towards 2030	I	
Australia	National Mineral Exploration Strategy	I	
Romania	The Strategy of the Mining Industry for 2004 - 2010	I	
South Africa	Strategic Plan 2014/19	I	
India	National Mineral Policy (for non-fuel and non-coal minerals)	I	
Jamaica	The National Minerals Policy - Fostering sustainability in Jamaica's minerals industry	II	**Mining for Development (12 documents)**
Cook Islands (NZ)	Cook Islands National Seabed Minerals Policy	II	
Denmark (Arctic)	Kingdom of Denmark Strategy for the Arctic 2011– 2020	II	
France	Mineral resources and development in Africa: Strategic guideline document	II	
Greenland	Greenland’s oil and mineral strategy 2014-2018	II	
Kenya	Minerals and mining policy	II	
Liberia	Mineral Policy of Liberia	II	
Namibia	Minerals Policy of Namibia	II	
Tanzania	The Mineral Policy of Tanzania	II	
Uganda	The Mineral Policy of Uganda	II	
Kyrgyz Republic	Medium and long-term strategy of mining industry development of the Kyrgyz Republic	II	
Rwanda	Strategic Plan 2010 - 2013	II	

Canada	The Minerals and Metals Policy of the Government of Canada	III	**Our Resources for our Industry (7 documents)**
Czech Republic	The Raw Material Policy of the Czech Republic in the Field of Mineral Materials and Their Resources	III	
Finland	Finland's Minerals Strategy	III	
Greece	National Policy for the Exploitation of Mineral Resources	III	
Norway	Strategy for the Mineral Industry	III	
Portugal	National Strategy for Geological Resources - Mineral Resources	III	
Sweden	Sweden's Minerals Strategy	III	
Denmark (waste)	Denmark without waste	IV	**Closing cycles, securing Supply (6 documents)**
Germany	The German Government's raw materials strategy	IV	
Ireland	Towards a Resource Efficient Ireland - A National Strategy to 2020	IV	
The Netherlands	Policy Document on Raw Materials	IV	
United Kingdom	Resource Security Action Plan: Making the most of valuable materials	IV	
United States of America	Critical Materials Strategy	IV	

Note: Austria has a resource plan and strategy, both of which we analyzed as part of the same strategy; Denmark has a waste strategy and a strategy for the Arctic, both of which fulfilled our selection criteria and were thus included in the sample as two separate strategies covering two different regions.

In contrast to the clusters suggested through the cluster analysis, Rwanda and the Kyrgyz Republic move from cluster III to II, since they are positioned left of the y-axis, and India and South Africa move into cluster I, since they are positioned above the x-axis.

Annex 5: Cluster analysis

The following cluster dendrogram resulted from the initial cluster analysis.

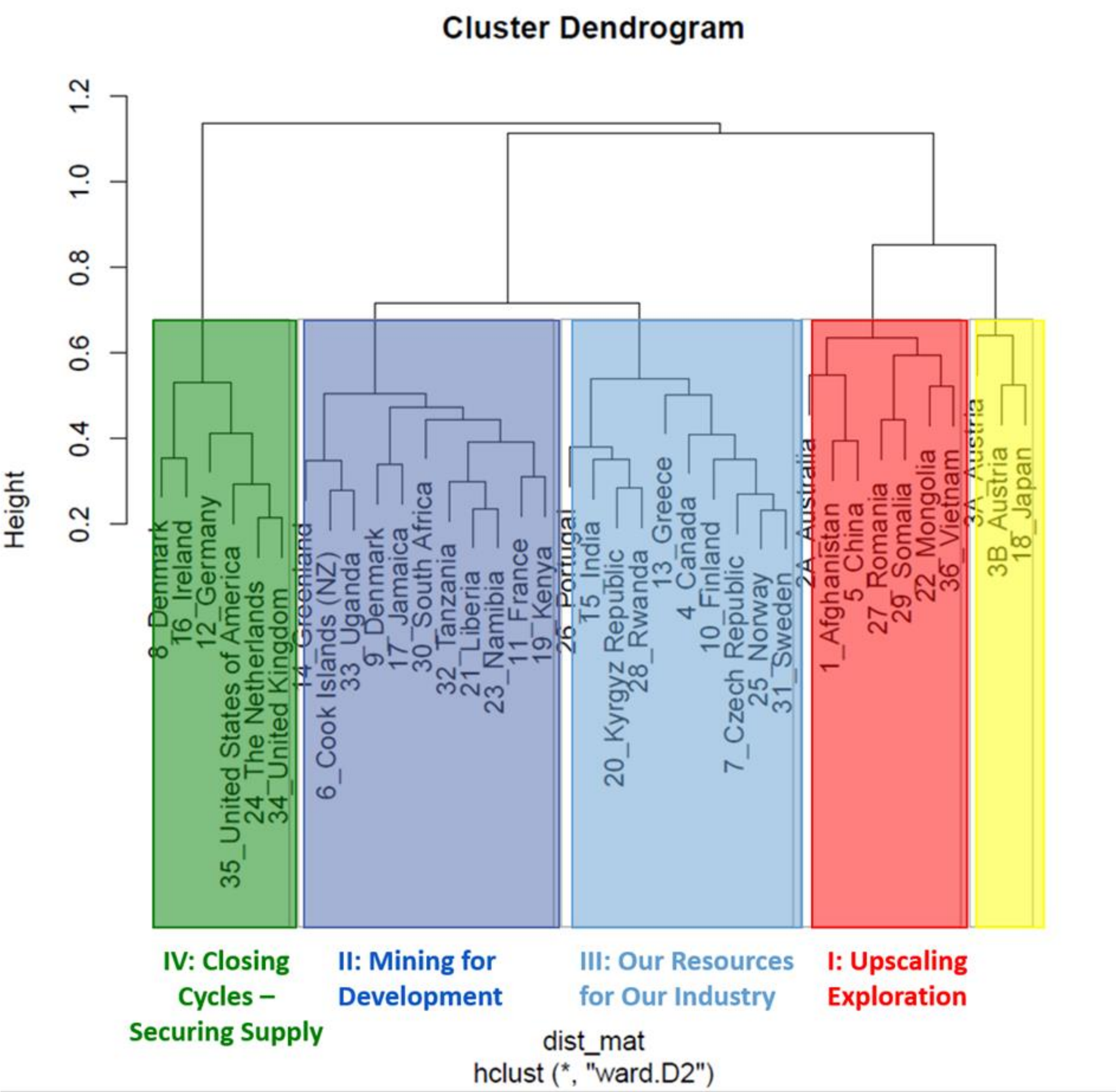

Fig. A 1: Cluster dendrogram

Annex 6: Cluster descriptions

Complementing the overview in table 1 of the manuscript, the four clusters are described in more detail below with regard to their geography, resources and economic situation.

I. Upscaling exploration

Strategies in cluster I *(9 documents in total)* have been issued through countries that form the most diverse group regarding their geographic position and (geo-) political situation. They are rather resource-rich, often with large newly discovered reserves and/ or still unexplored areas. With the exception of Australia, they can be considered as "emerging economies" with varying degrees of industrialization and resource demand. Though not limited to those, the cluster has the highest share of Asian countries. Strategy documents of countries in cluster I are exclusively focusing on exploration and trade, and use sustainability mainly in the sense of sustained resources. No strategy is covering the phases of product design & manufacture, product use and secondary production or interlinkages between phases. None of the strategies expresses the need for an overall transformation of patterns of resource use and consumption, and only a quarter expresses an urgency to act, compared to two thirds in clusters III and IV.

II. Mining for Development

Countries in cluster II *(12 documents)* are similar to those in cluster I concerning their resource-richness. Countries tend to be economically weaker and have a lower demand in industrial raw materials for their own industries. In two cases, the strategies focus on areas outside the country that are less industrialized (France's strategy for Africa and

Denmark's for the Arctic). The cluster includes the majority of African countries from our sample. While strategy documents in this cluster share their clear focus on primary production with those in cluster I, cluster II strategies concentrate more on mining than exploration. Situated below cluster I in the MCA biplot, they include aspects associated with the sustainability rationales "operating sustainably", but also "contributing to sustainable development" such as community development, participation and distribution. In contrast to cluster I, almost all strategies formulate a vision. Mineral wealth is seen as an opportunity for prosperity.

III. Our Resources for our Industry

Strategies in this cluster *(7 documents)* have been issued by countries that are generally rather resource-rich and rather economically strong and have a high demand in resources for their local industry. Most countries in the group are European, plus Canada. Situated in the lower right quadrant, but very close to cluster II, strategy documents of countries in cluster III include more measures from later life-cycle phases and mostly use sustainability in the sense of operating sustainably (but not, in contrast to cluster II, in the sense of contributing to sustainable development). The overall aim is to secure and develop own deposits for the local industry (all 7 documents), while at the same time securing additional supply from abroad (5 strategies issue measures for transport and trade) and keeping existing raw materials in the system (6 strategies aim to foster secondary production). All of them mention supply risks and competition as challenges.

IV. Closing Cycles, securing Supply

Strategies in cluster IV *(6 documents)* have been issued by countries that are generally less rich in resources, but economically strong with a high demand for industrial raw materials. Situated towards the right end of the x-axis, strategy documents of countries in cluster IV are addressing all life-cycle phases rather evenly, putting the overall focus on technological progress across the whole value chain. Compared to the other clusters they have the highest percentage of documents addressing the EoL-phase and secondary production as well as interactions or interlinkages between life-cycle phases. Half of the documents in the group express a need for an overall transformation of resource use patterns. Interestingly though, and especially in contrast to clusters I and II, only a very small share of documents makes some kind of visionary statement or describes a desired future state.

Annex 7: Further results from the analysis

Referring to ch. 3.2.1 of the manuscript, the graph below shows topics, goals and challenges as brought up through the SDGs covered by each of the strategy documents

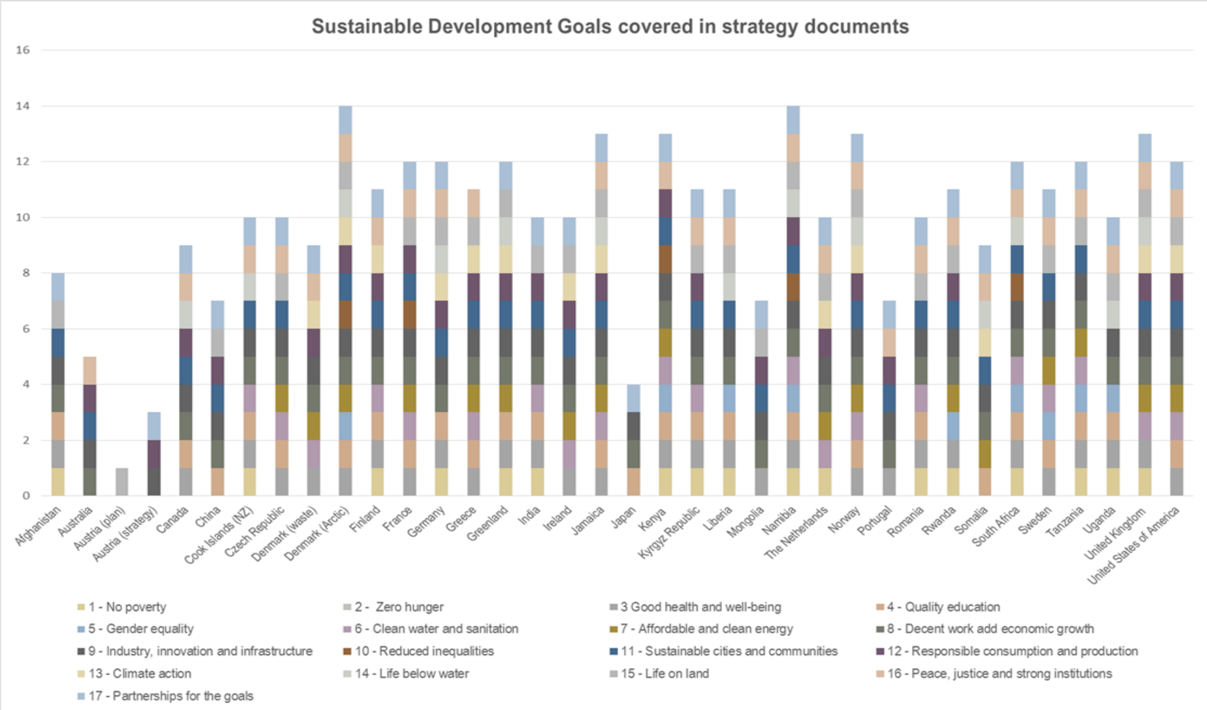

Fig. A 2: SDG coverage of the strategies in our sample

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5 SYNTHESIS

5 Synthesis

5.1 Design features for strategies towards a more sustainable metal production and use

5.1.1 General findings on strategies

The results confirm my assumption that existing strategic approaches that intervene in metal production and use are lacking a clear orientation towards fostering sustainability. Strategies need to define and actively incorporate sustainability to make sure that all interventions are directed towards this goal. Structuring strategies as transition strategies can support this orientation towards sustainability (P4), when they include a defined current and target state and activities directed towards reaching this desired future state that are informed by a clear and tangible theory of change. Strategies have the potential to provide a flexible and transparent approach to governing complex and border-crossing issues like metal production and use, but they still face challenges regarding the very heterogeneous contextual conditions existing in different countries or on the various operational levels (including the corporate level) (P3). The four clusters of strategic approaches (P4), which differ concerning their overall objective, focus on specific phases of the life cycle and incorporation of sustainability principles, can serve as a first orientation for the national level. They support the design of strategies that are comprehensive, but focused and embedded in the larger context of their implementation. The findings of P3 and P4 partly complement each other in this respect:

- Single strategies from the sample analyzed in P4 can be considered to be on one of the paths suggested in the scenario analysis (P3). Australia's exploration strategy (Geoscience Australia, 2017), for example, supports the idea of aligning state activities with the engagement of the private industry (A World of Cooperation) (P3). At the same time, it clearly lacks a consideration of other life cycle phases and an orientation towards sustainability, so that it will contribute (only) to reducing criticality, rather than contribute to the deep change in resource production and use that the scenario could achieve (P4). Denmark's waste strategy (The Danish Government, 2013) puts the focus on recycling as suggested in the "Recycling Society" scenario (P3), but lacks concrete suggestions for the specific challenges associated with recycling metal-containing products (P4).

- The shell scenarios used for the robustness appraisal in P3 (Raskin et al., 2010; Tellus Institute, 2009) can support the design of adaptive strategies, as they allow to consider different surrounding conditions that strategies should prepare for or be able to adapt to.
- Both articles discuss different approaches, measures and mechanisms to guide metal production and use. While P3 shows their interlinkages and emphasizes the consideration of both systemic and future relevance of these approaches, the results of P4 pronounce smart reasoning concerning the sequence of actions and their effect over time. The sequence of actions should consider the time scales of their implementation as well as balancing the need for (i) urgent response to existing challenges and (ii) long-term transformation, emphasizing an assessment and anticipation of the kind of change that interventions bring about. The findings on temporal diversity can inform both the impact of actions (temporal impact assessment) (P1) and potential path dependencies that strategies should consider along the value chain (e.g. maintenance intervals influencing product life time) (P2).

The variability in existing strategies makes it difficult to compare approaches or assess their potential impact. This can partly be met by understanding these differences through the temporalities of the interventions (P2). Besides contributing to a deepened system understanding, the findings of P1 and P2 also support interventions that are 'making good use of time' ('kairos') (Held and Geißler, 1995; Kümmerer, 1997; Reisch, 2001). Measures implemented at the right point in time and in the right place can support a quick response to disturbances or speed up a desired, more profound change. As an example, shortage in supply may spark innovation especially when properly supported (P1). These considerations closely link the results to the concept of leverage points as places to intervene in a system (Abson et al., 2017; Meadows, 1999). They inform strategy making, where interventions targeting shallow leverage points, but leading to quicker success (e.g. for issues that need immediate attention), can kick-start other, deeper levers to achieve profound long-term change.

5.1.2 Design features

As shown in chapter 2 of this dissertation, tackling the challenges associated with unsustainable metal production and use means (i) to deal with the multitude of interventions on different levels, by different actors, and with different foci, (ii) to clearly direct actions towards sustainability and support a fundamental change in existing patterns of metal production and use, and (iii) to design interventions with a long-term perspective, bearing in mind the natural limits of a system, but also the resilience it gains through its flexibility. In short, this implies three essential needs that future strategies should tackle: (i) managing complexity, (ii) achieving sustainability and (iii) embracing change (see Fig. 4). In the following, I apply these findings to the design of strategies for intervening in metal production and use, particularly considering the findings on the role of temporal diversity.

Strategies should be designed in line with the following six generic design features that result from the findings in chapter 4. To achieve a certain outcome, the process of designing and implementing a strategy is as important as its content. Thus, each of the design features responds to one of the defined needs and either relates to aspects of process or content. A design guideline links and shortly explains the two design features referring to each of the three needs (Table 2) *(compare e.g. Luederitz et al., (2017) concerning the interlinkages of content and process for the case of transition experiments).*

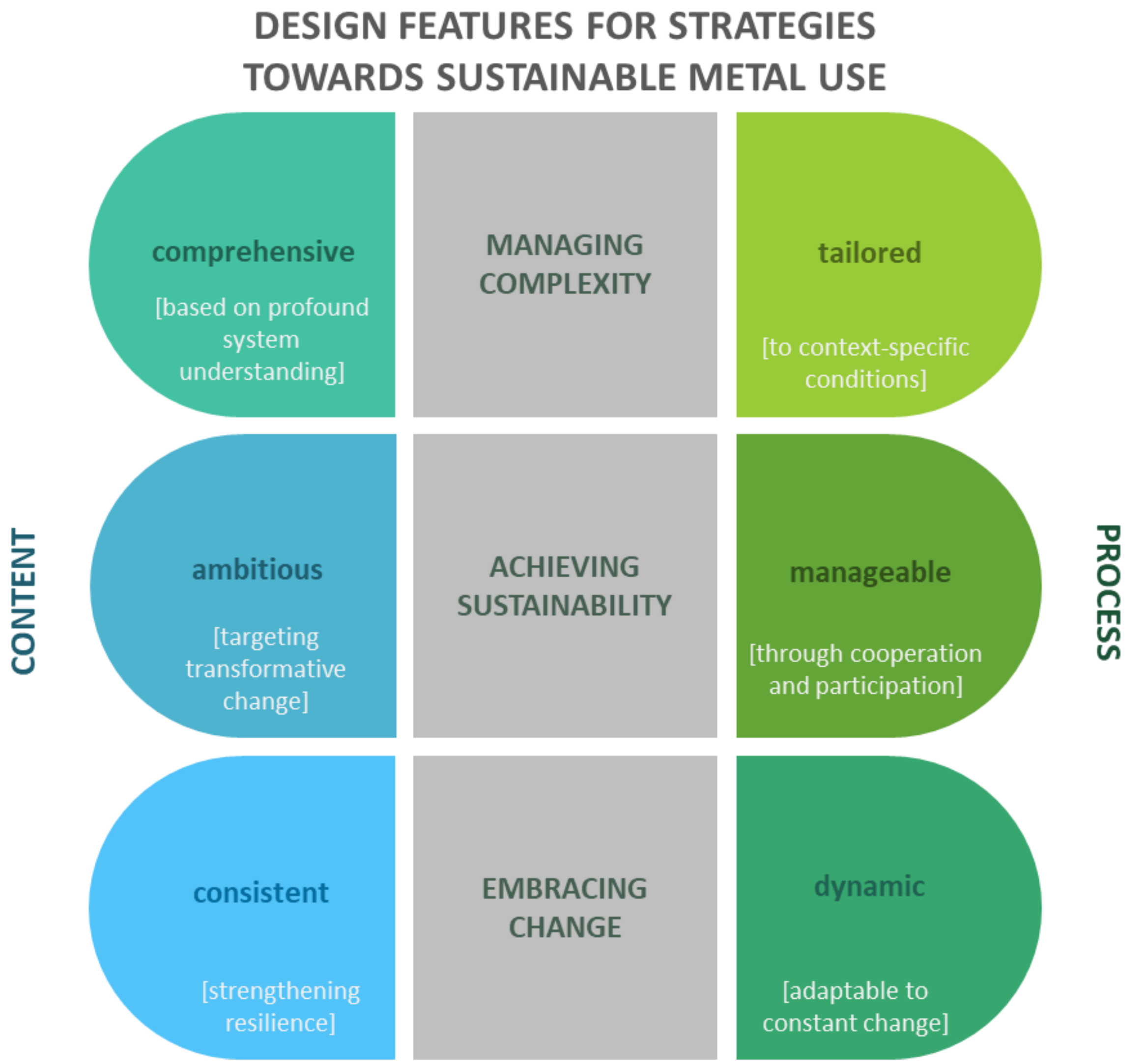

Fig. 4: Overview of design features for strategies towards sustainable metal use

Table 2: Needs to tackle by future strategies as derived from our analysis, resulting design guidelines and design features

Essential need	Design guideline	Design features
MANAGING COMPLEXITY	Design strategies based on a **profound understanding of the system and** its interrelations, but bear in mind **context-specific characteristics.**	*Comprehensive, but tailored.*
ACHIEVING SUSTAINABILITY	Design strategies to achieve **fundamental change** in a **cooperative and inclusive manner.**	*Ambitious, but manageable.*
EMBRACING CHANGE	Design strategies to **strengthen resilience** in a **constantly changing** environment.	*Dynamic, but consistent.*

In the following, I will refer to each of the three essential needs (Table 2) and related design features (Fig. 4) and describe how my findings can concretely inform (future) strategy design, showing, where and how the generic criteria can unfold relevance for the case of metals. Each chapter follows the same structure and (i) shortly sketch the background and relevance as shown through the results, (ii) describes general implications for strategy design and (iii) illustrates how my results can contribute to the operationalization of the design features for the case of metal production and use.

#1: MANAGING COMPLEXITY

Guideline: Design strategies based on a **profound understanding of the system and** its interrelations, but bear in mind **context-specific characteristics.**

Resulting features: Comprehensive, but tailored.

#1_A: Background and relevance

Achieving fundamental change in how we use (rather than 'consume') (Exner et al., 2016) metals along the whole life cycle necessitates a large variety of activities to tackle the challenges on very different operational scales and in various "intervention fields" (Prior et al., 2013; Wäger et al., 2012). Often, these activities are highly interlinked (P3) or affect other transformation processes (Schindler, 2016). Existing national strategy processes are often insufficiently embedded in the overall governance structures, especially concerning connections to other sectors and levels (P4). Existing approaches are very heterogeneous, as are the potential interventions and solutions that could be considered in strategies (P3) (P4). Strategies should acknowledge this complexity, but must still be sufficiently focused to provide concrete guidance for action and consider existing differences in the regulative mechanisms and political systems they target (P3). Otherwise, processes can become inefficient and fail to consider characteristic details (Holism Panacea - P4) (Kunz et al., 2013). This holds especially true for the specifics of critical metals like indium, which are often produced as co-products of other mining processes, so that an increase in supply is determined by an increasing demand and production of the major metal (Werner et al., 2017).

Strategies can manage this complexity by being designed (sufficiently) comprehensive and systemic, but tailored to context-specific conditions.

#1_B: General implications for strategy design

Complexity and uncertainty are common characteristics of sustainability problems (Grunwald, 2010). Using models and system dynamics to deal with both uncertainty and complexity is a common feature of sustainability science (Kates, 2001). The design features 'comprehensive' and 'tailored' refer to the strategy's scope throughout the *description of the current and target state* as well as the suggested interventions of the *transition strategy*. They provide *system knowledge* (ProClim, 1997; Hirsch-Hadorn et al., 2008) as the necessary basis to select appropriate interventions and to prepare their implementation considering the specific conditions and characteristics of the system they aim to change.

Regarding the strategy's *content*, the depiction of the current and target state should reflect a profound understanding of the system and its dynamics, resulting in a detailed and precise description of the initial situation, a complex vision and a concrete and differentiated transition strategy (P4). A clear description of the motivation for issuing the strategy, a reasonably defined time frame and an informed prioritization of measures based on their feasibility and potential impact are concrete results of such a systems-based understanding (P4). Strategies should have a clear focus, but consider the broader (systemic) context. 'Clear focus' means that a strategy should be (just) sufficiently comprehensive: Understanding a system's dynamics helps to identify the most relevant drivers (including those driving unsustainable resource use (P4) (Hirschnitz-Garbers et al., 2016)) and to prioritize actions in response to the most pressing challenges (P3) (P4). 'Broader (systemic) context' refers to (i) other sectors and processes as well as (ii) other life cycle phases. 'Considering' must go beyond mentioning, but should make clear, where, how and when actions may affect each other, and incorporate uncertainties (P1) (P4).

Regarding the *process of strategy design and implementation*, the economic context and the role that resource production plays in the national economy have a strong influence on motivation and ways of implementation (P4). The strategy's motivation or purpose and its concrete subject define the system boundaries: Different actions are needed or suitable for different (groups of) metals. Other mechanisms or dynamics are in place for mining than for recycling

(P4). The geographic and political context, in which a strategy is embedded, shapes the overall policy style of a country (Barteková and Kemp, 2016). This has concrete consequences for interventions concerning the role of the state and its relation to other actors as well as to other states (P4). A 'strong state' will suggest other forms of intervention than one that relies on the self-regulation of the market (P3).

#1_C: Operationalizing the design features 'comprehensive' and 'tailored' in strategy design

A clear structure – as suggested in P4 – supports a strategy's internal coherence, allowing to set the right focus and following this focus throughout the strategy. This includes describing and defining the current and desired target state, and a transition strategy informed by a theory of change that shows how exactly the intended change could occur. The Sustainable Development Goals (SDGs) have been explicitly linked to resource governance (Ali et al., 2017; Waage et al., 2015), sustainable chemistry (Kümmerer and Clark, 2016; Weiser et al., 2017) as well as mining and geology (Gill, 2017; Lewis and Flynn, 2016). They can provide further guidance in the attempt to grasp comprehensively all relevant issues in relation to the purpose and context of the strategy, but should specifically consider the interplay of the various fields of actions and potential trade-offs that might arise from trying to reach the defined goals (Nilsson et al., 2016). Just mentioning issues outside the strategy's frame like a 'checklist' is insufficient (P4).

The four clusters of countries – representing different strategic approaches on national level – identified in P4 differ specifically in how (comprehensively) they cover life cycle phases, which highly influences strategy design and the interventions they suggest. These clusters can serve as orientation for other countries to develop strategies that consider context conditions and historically developed policy styles. The latter influence the role of the state in relation to other actors and are rather resistant to change themselves (P4), hinting at patterns of change that may be difficult to influence (P2). Both P3 and P4 list and categorize a variety of challenges that strategies could meet, such as supply risks, dissipation and environmental damage, which might help to move a strategy's focus beyond the market-related challenges already tackled by most. The main 'building blocks' of a comprehensive resource policy named by Exner et al. (2016) (see chapter 2) can be of further guidance here. A deepened system understanding helps to design strategy interventions tailored to the most pressing challenges for the specific case. These may differ among countries (or clusters) (P4) as well as depending on the strategy's focus, as different challenges may apply to critical metals than to major metals (P3).

Our findings on temporal diversity emphasize the role of observation and perception for identifying a system's inherent times. Systems must be observed within appropriate time frames to enable a differentiation of naturally occurring change from (unintended) disturbances (P1 + P2). Temporal scope also links to the spatial scope or operational level of a strategy. The temporalities associated with a strategy on local level might be easier to oversee – and time scales might be shorter – than those on a global scale. This illustrates a direct link between the system features time and space and the process of defining a strategy's scope tailored to context. The temporal extension of the strategy, including the time it extends into the past in describing the situation and motivation, has a direct influence on how well the suggested actions are tailored to the conditions of the specific case (P4). Even though a more sustainable metal use asks for a long-term approach, defining a long strategy horizon is insufficient (P4). This holds especially true since uncertainty increases with longer time scales, making it more difficult to anticipate unintended consequences or to determine the cause and effect of actions (P1). System understanding, therefore, must also include the temporal system characteristics and their interconnections. Step 1 of the time-in-transformation approach (P2) ('Identify and relate temporal features') supports the identification of temporal features such as rhythms or temporal webs and the resulting path dependencies that might influence (i.e. support or hinder) the implementation of strategy actions, which once more emphasizes the importance of considering all life cycle phases and their interlinkages, even when the suggested interventions focus on single phases (P4). This has special value with regards to understanding the complex interlinkages in metal production and use, for which the step allows (i) to consider potentially different time scales in the various spheres and sectors affected by the strategy (P2), but also (ii) to perceive unintended changes and disturbances in time to react appropriately (P1). Step 2 ('Differentiate four types of change patterns') helps to detect and perceive (and properly assess) relevant patterns of change (P2) to define an appropriate overall time frame for the strategy.

Scenarios and scenario analyses can be a way to enhance system understanding further. On their basis, we can identify the relevant system characteristics that need to change and, moreover, assess an intervention's systemic relevance to make sense of the multitude of possible interventions and intervention points (P3). In doing so, scenarios can also be relevant components of transition processes (Wiek et al., 2006), informing the definition of an appropriate sequence of transition actions (P4) (Kay et al., 2014) against the background of a defined temporal scope.

#2: ACHIEVING SUSTAINABILITY

Guideline: Design strategies to achieve **fundamental change** in a **cooperative and inclusive manner.**

Resulting features: Ambitious, but manageable.

#2_A: Background and relevance

Achieving a more sustainable production and use of metals necessitates fundamental changes on a variety of levels and in many different sectors that call for "a strategy of incremental change with a transformative agenda" (Patterson et al., 2017). This includes a reduction of the negative social and environmental effects as well as targeting absolute decoupling (Giljum et al., 2014; Kümmerer, 2017). At the same time, metals are essential for a variety of technologies contributing to the transformation towards sustainability. Strategies should thus bear in mind this two-fold relationship of metal use and sustainability. Targeting the needed far-reaching changes means to intervene in a variety of complex systems and affecting and involving a high diversity of actors. Such a large-scale transformation will not be done in one step, but needs to keep in mind the overall goal of achieving profound change even in defining measures targeting quick rather than deep change.

Strategies must thus find the right balance between motivating for and effectively leveraging transformative change and demonstrating who can contribute what to effect such change by being ambitious, but manageable.

#2_B: General implications for strategy design

Sustainability is a normative concept with strong implications for (sustainable) resource production and use. A sustainability perspective on metal use must consider an equitable distribution of value among present and future generations (Moran and Kunz, 2014; WCED World

Commission on Environment and Development, 1987) as well as the planet's carrying capacity. The design features 'ambitious' and 'manageable' mainly relate to the defined target state and the theory of change that guides the overall idea of how change could be achieved. They provide *target knowledge* to guide strategic actions as well as *transformation knowledge* concerning a cooperative process design that enables mutual learning (ProClim, 1997; Hirsch-Hadorn et al., 2008).

Regarding the strategy's *content*, formulating strategy objectives that are ambitious, but informed by a profound understanding of the system, are the basis for guiding the strategy's focus, objective and suggested actions. This calls for a clearly defined sustainability understanding that relates to the specifics of metals employed throughout the strategy as well as a comprehensive idea of what transformative change does entail.

Regarding the *process of strategy design and implementation*, manageable relates to participation in the strategy formulation process, to considering state and non-state actors and to reasonably embedding the strategy within its (international) context. Strategies should be clear on where they relate to sectors and actors outside the strategy's scope, make use of these interlinkages and enable mutual learning across strategy processes, levels and fields of intervention. They should assign clear responsibilities and address who is meant to take which kind of action.

#2_C: Operationalizing the design features 'ambitious' and 'manageable' in strategy design

Involving other stakeholders besides the state into the strategy formulation can improve the description of the complex interlinkages in defining the current state and make sure that all relevant actors are addressed and understand their role in the transition process. Visioning can be a useful tool to define the desired future state and the objective of the strategy in a cooperative process to thus make sure that relevant actors are sufficiently represented and contribute their individual expertise (P2), including expertise on the potential future relevance of certain interventions and technologies (P3) (Jackson et al., 2014; Lederwasch et al., 2011). Such a process can also lay open the underlying motives that drive different actors (P4) (Wiek and Iwaniec, 2013) and contribute to an elaborated understanding of their needs, but also the inherent time scales of perception and action of actor groups (P1). This can minimize perception lags and may avoid potential temporal misfits in the strategy implementation process, and can improve knowledge management and information flows, since context influences an actor's perception of occurring changes as well as his individual scope of action (P2). Promoting international agreements can support coherent action towards a shared goal, where different regulatory national systems would otherwise inhibit international cooperation. The African Mining Vision is a good example for such a guiding process across national borders (African Union, 2009; Ambe-Uva, 2017).

Achieving sustainability – in the sense of 'sustaining resources' and 'operating sustainably' as well as equitably sharing values and burdens – should be the central driving force of such a vision, providing guidance for all other goals and actions formulated under this umbrella. Existing strategies make use of the term sustainability in many different ways and rarely incorporate the concept comprehensively and coherently, which would mean to consider, among other, all three sustainability rationales identified in P4 (sustained resources, operating sustainably and contribution to sustainable development). The works of Moran and Kunz (2014) serve as a good orientation to define the necessary next step to be taken towards both operating sustainably and achieving sustainable development in resource production and use in terms of equitable distribution of value. (P4) Defining a target state must also consider what can be achieved. For the case of metals, this is especially relevant concerning dissipation, which cannot be fully avoided, but must be reduced in its degree to minimize losses (Kümmerer, 2016).

Achieving a more sustainable metal production and use is a profound long-term change project that will not be accomplished in just a few years, but it still calls for immediate action taken in some aspects. Strategies must therefore define, which objectives demand 'quick' or 'deep' change. This puts the potential impact of actions into the center of attention. Understanding change patterns, including what can and cannot be easily influenced, is a necessary condition for smart reasoning in this respect (P2). Timing decisively influences impact (P2). Step 2 of the suggested time-in-transformations-approach (P2) supports this by considering how long it might take for actions to show an effect and what should be avoided because unintended impact cannot be estimated properly (P1) (P2). Different measures can drive different kinds of change, also depending on the place of intervention in the system (Abson et al., 2017; Meadows, 1999). Existing strategies lack leverage points targeting a system's intent, which means that measures targeting design, feedbacks or parameters of the system are not driven by the idea of changing the defining paradigms. This results in strategy actions that keep up the status quo or rather reinforce unsustainable patterns of metal production and use, which Meadows describes as counter-intuitive: The chosen measures can be appropriate to drive action, but possibly do so into the wrong direction (Meadows, 1999). Involving a variety of stakeholders into the strategy formulation process would also mean that strategic actions can be purposefully assigned to those who have the largest leverage or can influence system variables most effectively (P2).

In a nutshell, decision-makers should (i) ensure that a strategy's desired target state is guided by the concept of sustainability and clearly states what makes the target state 'better' than the current state, (ii) make use of the concept of leverage points to purposefully intervene in the system according to the desired outcome, and (iii) clearly state, where and how the strategy is embedded into the larger context concerning connected sectors as well as other regulative levels. The research on transitions and transformations (see chapter 2.1.2) can inform strategy design concerning the process of structuring the intended change (differentiating phases) and in making use of windows of opportunity that may facilitate change.

#3: EMBRACING CHANGE

Guideline: Design strategies to **strengthen resilience** in a **constantly changing** environment.

Resulting features: Dynamic, but consistent.

#3_A: Background and relevance

Making sense of the multitude of possible interventions and the implications they may have on different spatial and temporal scales demands smart reasoning in selecting and prioritizing measures to ensure that actions taken towards more sustainable metal production and use remain within the planetary boundaries or its 'carrying capacity' and avoid irreversible change (Low et al., 1999; Rockström et al., 2009). (Natural) Systems are characterized by constant change. Change can either be intended or unintended, either an inherent feature of a (natural) system or the sign for its disturbance (P2).

Strategies can embrace this diverse understanding of change through a dynamic design that allows continuous adaptation to occurring change and at the same time corresponds with the natural flexibility of systems to gain or strengthen its resilience.

#3_B: General implications for strategy design

Systems gain some degree of resilience from their rhythmic nature (Held, 2001), which means they can adapt to changes within a certain range, but may be irreversibly disturbed once this range is exceeded (P1). Strategies should thus actively work with the fact that systems are subject to constant change. The design features 'consistent' and 'dynamic' have strong implications mainly for the transition strategy and suggested actions. They contribute to an improved *transformation knowledge* regarding the design of adaptive and resilient strategies as well as the prioritization of some interventions over others based on a profound understanding of the desired target (ProClim, 1997; Hirsch-Hadorn et al., 2008).

Regarding the strategy's *content*, interventions must consider a system's (temporal) characteristics and dynamics and their potential effect. Effect, in this respect, has two dimensions: (i) anticipating and considering or avoiding unintended side effects, and (ii) the magnitude of the intended change. Depending on the defined target state, properly timing an intervention can mean to either keep disturbances as low as possible or to make use of the decreased resilience of a system that one intends to fundamentally change (P2).

Regarding the *process of strategy design and implementation*, strategy design should consider the non-linearity of both metal production and use and transformation processes. A linear understanding of time leads to linear strategies, which are less resistant to change. Strategies should incorporate a balanced mix of actions that meaningfully complement each other (including both technology and governance) to contribute to the robustness of a system when facing changing environments (P3) and improve its adaptive capacity (Clark et al., 2016; Folke et al., 2005).

#3_C: Operationalizing the design features 'consistent' and 'dynamic' in strategy design

Designing strategic interventions that are consistent with the affected system(s) emphasizes the role of system observation and understanding with regards to risk and uncertainty. The temporal features of point of time and duration help to determine the potential consequences and impacts of an event. (P1) To avoid temporal misfits, decision-makers should make sure that the time scales of strategic actions are in line with those of the system they target to not overstretch its flexibility. The three guidelines for interventions suggested in step 3 of the time-in-transformation-approach (P2) support such intervention design towards effective leveraging that is consistent with a system's resilience (P2). What is tolerable is also depending on the strategy's purpose, which might be to react to occurring change, to facilitate intended change or to prevent some kind of unintended change from occurring. Different kinds of measures can be suitable depending on how persistent existing patterns are, as shown for the case of behavior change, which may take longer to influence (P1) and is thus calling for the use of deep leverage points (P2) (P4).

Strategies should be designed with a precautionary approach and allow for quick adaptation to new insights on the risks and unintended adverse effects of actions, defining formal procedures for dealing with uncertainty (P1). This calls for a consideration of the largest relevant time scale (P2), even if it relates to a system that has links to, but is not part of the strategy's scope, as hazards may have their source outside the regulatory frame considered in the strategy (P1). Examples for a need to deal with risks and uncertainty from the case of metals are the yet largely unknown effects of dissipated materials on the environment (Kümmerer, 2016). Uncertainties exist also concerning the total amount of metals that can be extracted in the future. Existing estimations such as those based on the differentiation of resources and reserves *(compare e.g. USGS, 2016)* are often static, disregarding technological innovation and market dynamics, and partly speculative (Zittel, 2016).

A temporal diversity perspective on implementing a transition strategy also emphasizes actors' roles and their perception of an occurring change, but also of their perception of a need to react: Strategy actions must specifically support the change processes that need a speeding up, e.g. supporting research and development towards innovation for promising future technologies (P3). Explicitly defining the role and relationship of the state and the private economy can facilitate a sharing of responsibilities and avoiding over-regulation (P3) to better align the necessary interventions. Designing strategies that provide concrete guidance through the state, but leave room for other actions to evolve (especially private industry initiatives in eco-design and recycling) increases a system's capacity to adapt to changing conditions, making it more resilient (P3).

Social-ecological system research can further guide interventions concerning the consideration of the resilience, adaptability and transformability of a system (Folke et al., 2010). Transition management can inform (i) a strategy design that understands strategies as instruments to facilitate continuous improvement, including monitoring mechanisms, and (ii) transition actions that meaningfully build up on each other in a sequence of actions informed by the related patterns of change (P2) (P4). Understanding the underlying patterns of change of a system, including temporal irregularities and temporal extent (P2) serves two main purposes in the context of 'embracing change'.

- It supports the selection of appropriate indicators for monitoring progress (Moran and Kunz, 2014) and the definition of suitable monitoring intervals (P4).
- It informs both the kind and magnitude of change a system can tolerate and the potential magnitude of effects of intervening in the system (P2). Here, step 2 of the time-in-transformation-approach (P2) supports a proper timing of interventions in line with the desired outcome.

5.1.3 Further reflections on the design features

The design features are synergistic

To fulfill the defined needs of managing complexity, achieving sustainability, and embracing change, all design features must be considered as closely interlinked and synergistic:

- A clear structure and clearly formulated goal *(target state)* make a strategy tangible, increasing the chance it is understood and used by the relevant actors.
- A sufficiently comprehensive and specific system understanding is a pre-condition to defining interventions that are *consistent* with the system's (natural) flexibility and tailored to the desired outcome, which is ideally defined, framed and guided by sustainability considerations for metals.
- A comprehensive system understanding *avoids delays* in perceiving change and supports that decisions are taken in time, based on an informed system observation and perception of patterns of change (systemic relevance of interventions (P3)). Observing the principles of temporal diversity supports that decisions are taken at the right time

and consider interventions' future relevance (P3) in achieving the intended change towards more sustainable metal use.

- Designing a strategy in a specific *context* influences what is defined as the *desired outcome* and consequently predefines a strategy's focus and appropriate approach.
- The features *manageable* and *dynamic* directly relate, as defining clear addressees and involving several groups of actors in the implementation process also increases robustness (P3). The question of responsibility for guiding, perceiving and acting towards change links the features *manageable* and *consistent*.

The following **example** illustrates the interlinkages in applying the design features: Designing strategies that are *comprehensive,* but *tailored* asks for a clear prioritization of intervention options. System analysis shows that technological innovation in both recycling and mining rates rather low regarding systemic relevance, but very high in the perceived future relevance *(ambitious)* (P3), emphasizing the involvement of stakeholders' expertise in the design process *(manageable)*. Aiming towards interventions that sustain a system's resilience and applying a precautionary approach *(consistent)* means to prioritize recycling over mining, as the effects are easier to manage and oversee (P2). Following this, a strategy to reduce criticality threats and achieve a more sustainable metal supply should focus on improving recycling with appropriate measures, including suitable governance mechanisms *(tailored)*, but bear in mind the interconnections with other life cycle phases *(comprehensive)*, especially since primary production will still be needed. This could mean to design products in a way that increases their later recyclability to minimize dissipation (Kümmerer, 2016), but also to install innovative business schemes such as 'servicizing' the metal value chain (Prior et al., 2013) (P3) or product leasing, potentially redefining what is considered innovative and valuable (P1). At the same time, strategy design should bear in mind that achieving a "recycling society" (P3) necessitates behavior change, which can be a comparatively long and profound change process. Measures should thus target different leverage points including more shallow ones such as (i) incentives to speed up the desired change and (ii) interim actions to properly bridge the time until comprehensive recycling mechanisms and standards for product design are in place (P1). Clearly addressing and cooperating with multiple stakeholders including the private industry supports the implementation of suggested activities as well as the ability to react flexibly to occurring change *(dynamic)*. An example from practice are front-runner models and benchmarking approaches (Erdmann et al., 2011).

The design features connect time, transformation and strategic action towards a more sustainable metal production and use

Fig. 5, which is based on the time-in-transformations approach (P2), shows that the six design features consider and connect findings from all four research articles and actively link strategic action towards more sustainable metal use to existing understandings of transformation processes. Step 1 of the approach informs the preparation phase (P2), supporting a *comprehensive* approach that makes use of time as an integrative factor (P1) and resulting in a defined current state (P4) that is *tailored* to context and purpose. The target state (P4) defines *ambitious* goals to be reached, but should also consider that stabilizing the new system state (P2) calls for long-term considerations and precaution (P1). Both current and target state determine the transition strategy that aims to facilitate the actual intervention (P2). Both step 1 and 2 of the approach support a proper timing (P1) based on a deepened understanding of the system and patterns of change (P2). Following guidelines 1 and 2 of step 3 of the approach (P2) helps to navigate the change process and supports strategic action that is *consistent* with the system it targets in the intervention (P2). A *balanced* approach involving a variety of measures and actors supports robustness and keeps the strategy *manageable* in changing environments (P3). The actual transition process must consider delays and facilitate dynamic adaptation to changes that are in line with the system's natural flexibility (P1).

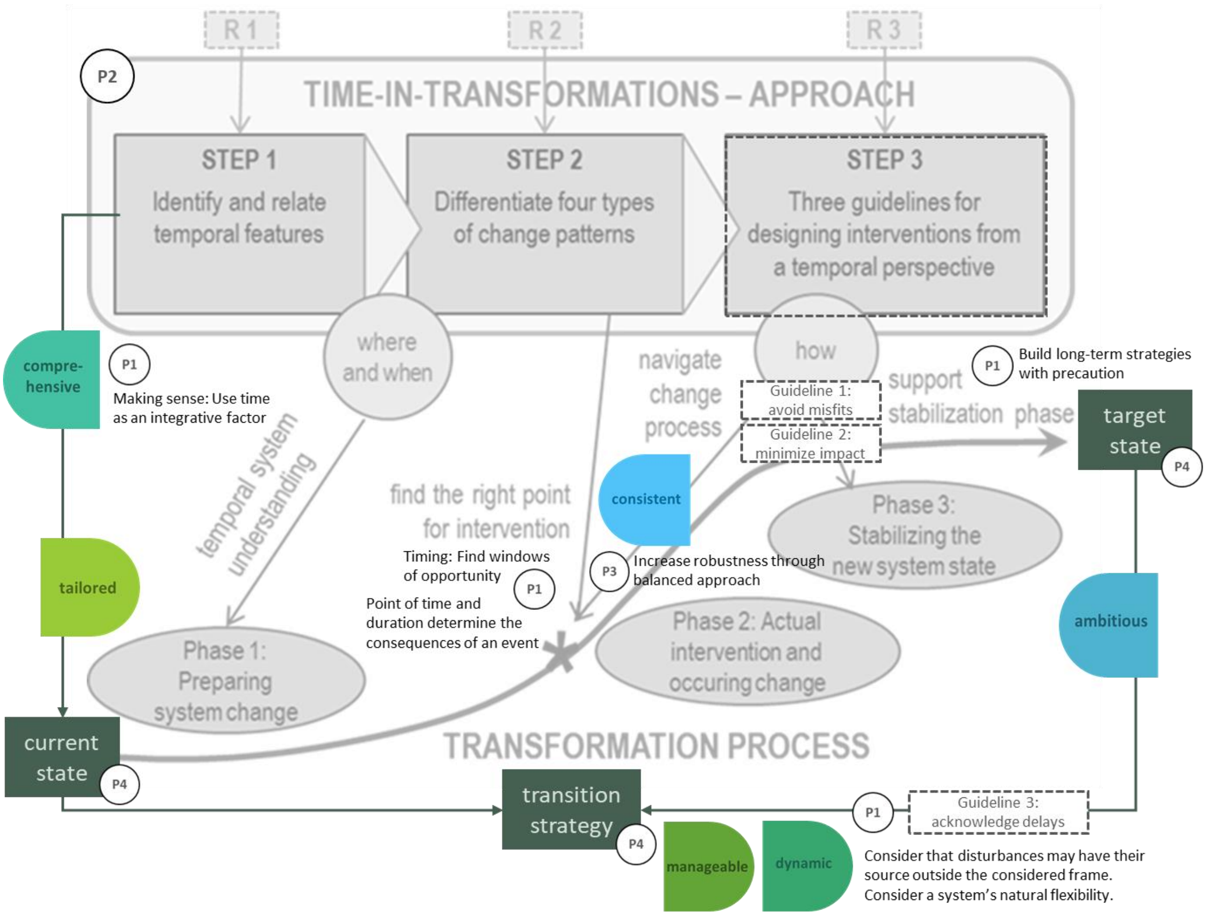

Fig. 5: Design features, strategy elements and findings on temporal diversity transferred to the time-in-transformations approach (light grey) (P2) that links time ecology and transformation research to support interventions in complex systems

The design features must be critically reflected upon their application

It is important to note that the design features depicted here are not necessarily comprehensive. Rather, they represent the core insights from the research presented in chapter 4 of this dissertation: The conceptual considerations are largely based on time ecology (Adam et al., 1997), applied to selected examples from either sustainable chemistry or the mineral-energy nexus. The scenario analysis focused on indium, incorporates the results from a selection of experts and refers to the year 2030. The analysis of strategy documents is limited to the national level and to those strategies that have been published in English language, many of which do not focus solely on metals, but on mineral resources in more general terms.

Depending on the context and the purpose a strategy should serve, further design features might become relevant. As an example, strategies also or mainly addressing individuals (e.g. consumers) will need to be tangible and maybe even motivational, similar to sustainability visions (Wiek and Iwaniec, 2013), which can be – and often already are – vital components of strategy making processes. Moreover, an application of the design features in strategy design processes will have to show how useful they are for processes on different operational levels from corporate to national and international, and where they need further operationalization and concretization. This is especially relevant considering the requirements that might result for strategy design out of the differences in – among other – where metal ore is mined, in which products metals are applied, or the product's life time and its recyclability at a specific point in time.

Formulated as rather generic design features, they unfold relevance only when they are applied to a specific case. Strategies focusing on critical metals might therefore define comprehensiveness differently than those that refer to metals or even mineral resources in general.

5.2 Time as a connecting element in the context of metals, transformation research and sustainability science

The research presented in chapter 4 has shown that – besides space – time is an essential component to be considered in understanding and intervening in systems. A diverse understanding of temporal issues can help to draw connections between the system of metal production and use and transformation processes by laying open their similarities and differences.

Processes of metal production and use share some (temporal) characteristics with the processes associated with transformations towards a more sustainable society (WBGU, 2011). Actively working with these similarities can improve system understanding across sectors and scales (P2), and interventions could profit from a design that suits the inherent time scales of both systems:

- Both are characterized by the need for taking action under uncertainty. For metals, there is a lack of reliable knowledge on substance flows, fate and behavior (over time) (P1) as well as on their future availability (Gordon et al., 2006; Werner et al., 2017). For many transformation processes, it is difficult to anticipate the long-term effects and potential trade-offs of innovations. Examples include rebound effects or tensions between conflicting goals as in the case of biofuels and food security (IFPRI, 2008). Moreover, we often lack the knowledge and experience of translating existing concepts into practice and bridging the gap between large-scale models and contextualized knowledge from e.g. local experiments (Lang et al., 2017). To deal with this uncertainty, strategy making approaches can be enhanced by (i) applying mechanisms such as the precautionary principle (P1) (P2), (ii) making use of methods like visioning (P4) or scenario analysis (P3), and (iii) cooperative approaches that enable mutual learning across disciplines as well as between science, policy and practice (P1) (P2) (Lang et al., 2012), and a sharing of tasks between stakeholders, including the state and private industry (P3).

- Both need to consider a multitude of interrelated actions, system variables and non-linear processes with various associated time scales and temporal features. To deal with this heterogeneity, interventions should be based on a profound understanding of the system(s) that may be informed by identifying the relevant temporal features and change patterns (P2). Acknowledging this diversity demands maneuvering between the need to (i) consider long time scales (e.g. behavior change, radioactive elements mined with Rare Earth Elements) and delays and (ii) flexibly respond to quick and unexpected changes (e.g. volatile prices, mining accidents), even when cause-and-effect relationships (Renn, 2008) are difficult to establish (P1) (P2). In that, they share a common feature of many complex systems that Meadows describes as counter-intuitivity of interventions (Meadows, 1999). Dissipation is agaian a good example here. Efficiency improvements might appear as an appropriate step towards more sustainable resource use, but if that means that products cannot be recycled to recover all materials and materials are lost for future use, using more (in the sense of a higher concentration) of a specific material per item would actually be the right choice (P1) (Kümmerer, 2016).

Such improved system understanding also shows us, however, where processes associated with metals and (societal) transformation have different patterns, are not (yet) aligned or difficult to align. Acknowledging the need to transform existing patterns of metal production and use would also mean, for example, to develop fundamentally new understandings of doing business (compare e.g. leasing, services) (P1) (P3). Based on the sample of existing strategies analyzed in P4, however, existing approaches to intervene in the system of metal production and use are insufficiently incorporating the need to transform prevailing patterns. The non-renewability of metals (at least in human time scales) stands in contrast to dissipative or metal-consuming structures that are largely in place (P1) (Held and Reller, 2016). Long-term global effects and risks cannot be fully met by rather short-term, often local socio-political approaches (P1). The (accelerating) pace of change on the planet through human activity (Steffen et al., 2015) is faster than the development of new pathways that could keep up the balance and ecosystem functioning (Adam et al., 1997).

Sustainability is adding a *direction* to this fundamental change; it is a normative component, which can again be operationalized also through the principles for incorporating temporal diversity developed in the presented research towards ‘making good use of time’ (P2).

The steps and guidelines of the time-in-transformations-approach (P2) are well suited to make use of these similarities, lay open the relevant differences and allow for their mutual consideration. To some extent, the results can then also contribute to the presented challenge of comparing the variety of strategic approaches and understanding the potential impact of interventions over time and relating to the desired outcome (P3) (P4).

Time is already implied in the literature as a component of transformation and transition research, e.g.:

- The capacities of resilience, adaptability and transformability in socio-ecological systems correspond well with the time ecology principles on how systems should be designed, e.g. considering the flexibility of natural systems (P1) (P2).
- Transition research mentions windows of opportunity to enable radical innovation to influence the system and both transition and transformation research consider differences in the duration, pace and magnitude of change processes (P2).

Still, there is a need for a deepened understanding for temporal disconnects of transformation processes and the according material basis, and for a more explicit consideration of temporal diversity in the research on processes of change that would make system observation and intervention design more comprehensive and precise at the same time (P2). As an example, the challenges associated with the growing impact of humans on the planet is mainly linked to an increasing spatial (in the sense of increasingly globalized) extension rather than impacts spreading in time (Held and Kümmerer, 2004; Steffen et al., 2015). This would include a consideration of threats from past events or the normal mode of operation, and a combined observation of the impacts of increasing spatial and temporal scales (Kümmerer, 1997).

The time-in-transformations – approach (P2) is a first step into this direction that introduces time as a functional component of analysis in the context of transformations (P2) for both understanding change and strategy development to facilitate sustainability transformation. Designed as an approach that considers the complex interlinkages of the mineral-energy nexus, it is especially suited also to making sense of a comprehensive consideration of metal production and use in its broader context. It aligns time ecology principles with the established multi-phase understanding of transformation processes (Geels and Schot, 2010; Olsson et al., 2014) and may inform the 'where', when' and 'how' of intervening in complex systems in order to achieve a transformation in the patterns of metal production and use towards sustainability (P2). The enhanced understanding of dynamics and interactions in changing systems that results from steps 1 and 2 of the approach supports a differentiation of transformational change from system-inherent patterns of change (P2). In doing so, it can enhance our understanding of 'context', which is considered a relevant factor in transition theory (Geels and Schot, 2010) as well as in the strategy analysis of P4 both for placing and timing interventions accordingly and to consider relevant interrelations with other processes and systems.

A closer consideration of temporal issues can thus complement the spatial perspective and make sense of the gap between urgency and long-term solutions that is an issue in many transformation processes towards sustainability (Patterson et al., 2017). It has the potential to change our 'attitude' towards change, taking uncertainties and constant change as given and rather understanding it as a strength than a challenge in designing interventions (P1) (P4).

In doing so, incorporating time does not only extend our understanding of transformation processes beyond the differentiation of phases and pace, which also informs the discussions on incremental and transformative change, urgency and long-term objectives (Feola, 2015; Patterson et al., 2017). It also provides guidance concerning the direction of these processes of fundamental change, e.g concerning systems' resilience and adaptability.

Summing up, the findings presented in chapter 4 of this dissertation contribute to both streams of sustainability research (Miller et al., 2014; Wiek and Lang, 2016):

1. Concerning an improved understanding of complex human-environment systems, the findings help to lay open the (temporal) disconnects of processes of metal production and use, the underlying material basis and the environmental impacts of actions. They also show that a linear link between those activities and the intended outcome cannot always be made (P1) (P2). Rather, a closer consideration of how

change is actually occurring should be the basis for a more flexible, dynamic approach to intervening in human-environment systems that are consistent with their inherent time scales and resulting resilience (P2) (P4). The *'Stoffgeschichten'* approach (Achzet et al., 2010; Böschen et al., 2004) is an example for grasping and communicating these complex interlinkages in a comprehensible way that could further support an understanding of the challenges in achieving more sustainable metal use.

2. Concerning the active contribution to sustainability transitions that sustainability research also targets, the recommendations for future strategy design emphasize the importance of cooperating with multiple stakeholders for the process of designing and implementing strategic actions towards more sustainable metal use (P3) (P4). This includes a mutual consideration of the expertise of relevant actors as well as their perceptions of change and the inherent time scales of their scope of action (P2). Strategies, in this context, should enable learning from and through the process of designing and implementing strategies, actively involving researchers not only as "generators of knowledge but also as knowledge-brokers and change agents" (Miller et al., 2014, p. 240). This can be achieved through dynamic strategy designs that allow capacity-building concerning institutional and organizational aspects (Held and Reller, 2016) and flexible reactions to disturbances and changing conditions.

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6

CONCLUSION & OUTLOOK

6 Conclusion and outlook

6.1 Towards bridging the transformation-material gap

The purpose of this dissertation was the identification of design features of strategies that contribute to achieving the fundamental shift towards more sustainable metal production and use, and exploring the role of temporalities for improving strategy design.

Achieving the 'material transition' is an essential building block of the Great Transformation towards sustainability that should include (i) minimizing the adverse effects associated with metal production and use and (ii) sustaining the availability of metals in a way that benefits present and future generations. Time matters in this respect - in close relation to space and as long as it is diversely understood in the sense of temporalities - to (i) understand the impact (duration and magnitude) of an intervention, (ii) recognize patterns of change that go beyond establishing linear, one-directional connections, and (iii) design interventions in a way that considers the resilience of a system.

My dissertation focused on strategies as a means to intervene in the system of metal production and use to support activities towards fostering sustainability along the whole life cycle. Such interventions should consider and respond to the challenges of (i) managing the complex interlinkages of processes and activities on various operational levels and spatial and temporal scales, (ii) providing clear guidance concerning the operationalization of sustainability principles, and (iii) keeping activities within the planet's carrying capacity and embracing constant change as an inherent system characteristic.

I identified six design features that respond to these challenges both for the strategy's content and for the process of formulation and implementation to establish strategies as means to actively contribute to achieving the material transition. The design features can be summarized in the following three guidelines:

1. Design strategies based on a profound understanding of the system and its interrelations, but bear in mind context-specific characteristics. *(Comprehensive, but tailored.)*
2. Design strategies to achieve fundamental change in a cooperative and inclusive manner. *(Ambitious, but manageable.)*

3. Design strategies to strengthen resilience in a constantly changing environment. *(Dynamic, but consistent.)*

The design features support strategy design concerning a comprehensive description of the current state that considers the individual situation as well as a formulation of the desired target state that guides the definition of the suggested transition actions, and can complement and improve existing considerations of resource governance.

My findings contribute to

- research on sustainable resource governance with recommendations for future interventions that facilitate target-oriented approaches towards fostering sustainability along the whole metal life cycle as well as mutual learning among stakeholders;
- transformation research through (i) new insights on understanding and making use of patterns of change by considering their temporalities to support capacity-building towards perceiving and embracing the dynamic character of sustainable development, and (ii) linking temporalities and the concept of leverage points as places to intervene in a system with different transformational effects;
- sustainability research a systems-oriented perspective on the interrelations of metal production and use and their social and environmental effects as well as design features for future strategy design as a step towards contributing to more sustainable metal production and use.

6.2 Outlook and further research

My research has confirmed - at least for the case of metals – that the material basis of transformation processes is still insufficiently considered in both research and practice. The development of design features for future strategies has shown how our understanding of processes of fundamental change could find closer consideration in metal production and use. Testing their applicability in different contexts would be a necessary next step that can shed light on the transferability of the results, including to other resource-related issues such as bioplastics or 'Power to X'. Accompanying processes of joint strategy development could be a promising field for transdisciplinary research on the matter. This would also offer an opportunity to test the transferability of the design features to other operational levels such as companies operating in the metal sector.

More research is needed on approaches that bring the material basis into closer consideration of societal transformation processes such as transition town movements or real-world experiments. This includes new approaches towards raising awareness for the significance and omnipresence of metals in our everyday life ('Metallbewusstsein') in the all metals age (Held et al., 2018). The concept of '*Stoffgeschichten*' (Böschen et al., 2004; Dießenbacher and Reller, 2016; Huppenbauer and Reller, 1996) has already proven useful in this respect. It has the potential to connect the research on metal production and use to the growing body of literature on the role of (transition) narratives (Luederitz et al., 2017) and storytelling (Fischer and Borner, 2018) that put the "protagonists, timelines, and places" (Veland et al., 2018, p. 41) into the center of attention.

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