Circular Resourcing: The Role of Mining in a Circular Economy

Konstantin Born

Wolfson College, University of Oxford

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Supervisor: Dr Caitlin McElroy

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Abstract

The global transition towards net-zero carbon economies is driving unprecedented demand for critical minerals essential for clean energy technologies. While the circular economy (CE) concept has emerged as a promising paradigm offering pathways to reduce demand for critical energy transition minerals through approaches, such as recycling and reuse, evidence suggests that downstream-focused approaches alone cannot meet the growing mineral requirements for global decarbonisation, necessitating continued primary extraction. This thesis examines how CE approaches can be applied to mining operations to address the dual challenge of securing critical minerals while minimising societal-environmental impacts.

Through three interconnected studies, this thesis broadens the scope of CE research by examining its application to the mining sector and resource-dependent regions, with a particular focus on Chile as one of the world's leading copper and lithium producers. The first study demonstrates that recycling alone cannot meet future copper demand, a key critical energy transition mineral, highlighting the need for alternative CE strategies beyond recycling. The second study investigates how CE approaches are being applied in the Chilean mining sector, revealing both innovative practices, such as tailings valorisation, seawater use, and equipment remanufacturing, and the rebranding of existing sustainability initiatives as CE interventions. The third study examines the spatial dynamics of CE transitions in Chile's mining territories, demonstrating how the spatial configuration of economic activities fundamentally shapes regional CE transitions.

The thesis makes three key contributions to academic knowledge. First, it extends CE scholarship by demonstrating its relevance for the mining sector and by improving conceptual tools to analyse CE implementation in primary production. Second, it advances the economic geography literature by showing how territorial characteristics and spatial configurations of economic activity shape CE transitions in resource-rich regions. Third, it contributes to sustainability transitions research by demonstrating the role of place-specific factors in shaping transition pathways. Together, these contributions underline that successful CE transitions in the mining sector and its host regions depend on addressing both operational practices within firms and broader spatial dynamics, providing crucial guidance for a more sustainable resource extraction model.

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List of abbreviations and definitions

APS – Announced Pledges Scenario

CE – Circular Economy

Circularity - A technical term referring to the magnitude or the proportion of flows with a circular character

CODELCO - National Copper Corporation of Chile

CORFO - Production Development Corporation of Chile

CircularTec - Circular Economy Technology Centre for the Northern Macrozone

CR – Critical realism

DP-MFA – Dynamic probabilistic material flow analysis

EEG – Evolutionary Economic Geography

ESG - Environmental, social and governance

EMF – Ellen MacArthur Foundation

EoL – End-of-life

GHG – Greenhouse gas

GPN – Global Production Networks

ICSG - International Copper Study Group

IWCC - International Wrought Copper Council

IEA – International Energy Agency

LCA – Life-cycle assessment

MFA – Material flow analysis

MT – Metric tonnes

NZW – Net Zero Emissions by 2050 Scenario

REG – Relational Economic Geography

REP – Extended producer responsibility

RO – Value retention option

RQ – Research question

STEPS - Stated Policies Scenario

OECD - Organisation for Economic Co-operation and Development

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1. Introduction

1.1. Context

The global shift towards net zero carbon economies necessitates a rapid transition to clean energy technologies over the next three decades, fundamentally altering the landscape of mineral and metal demand (Hund et al., 2020). As the energy transition drives a surge in demand for critical minerals used in electricity connections, electric vehicles, wind turbines, and solar panels, the mining and metals sector is under increasing pressure to meet this growing need. However, while the growing stock of secondary resources held in the anthroposphere offers opportunities to reduce the demand for primary mined minerals, there is growing evidence that the use of secondary resources will be insufficient to address the raw material requirements of the energy transition (Blagoeva et al., 2016; Born and Ciftci, 2024; Gregoir and van Acker, 2022). This has led to a renewed focus on primary mineral production, including the establishment of new mining operations and the expansion of existing mines (IEA, 2021).

This continued reliance on primary mineral extraction places the mining industry and mineral resource-dependent regions at a crossroads. On the one hand, there are growing expectations to deliver the required material inputs for large-scale decarbonisation by expanding the production of primary minerals, while on the other hand, there is increasing pressure from investors, commercial customers, local communities and consumers who are asking for assurances that raw material are sourced responsibly and that companies adhere to specific environmental, social and governance (ESG) standards (Caldecott, 2018; Franks et al., 2014; Kügerl et al., 2023; Lee et al., 2020). As a result of these pressures, there has been growing interest in challenging existing mining practices and sourcing the required raw materials from secondary sources (Moore et al., 2024; Xavier et al., 2023). However, large parts of global mineral and metal supply chains arguably still operate within a *linear* techno-

economic business model and pay limited attention to the whole life-cycle costs of material extraction and production (Lèbre et al., 2017; Upadhyay et al., 2021). Mining operations, therefore, continue to have significant negative environmental externalities (Lèbre et al., 2020; Watari et al., 2021a). To give but a few examples of mining's negative impacts on its environment, it is estimated that primary mineral and metal production already accounted for approximately 10% of the total global energy-related GHG emissions in 2018 and is rising further (Azadi et al., 2020; Greene, 2017), while mining also caused 7% of global deforestation and continues to be the fourth-largest driver of forest habitat loss and its associated climate impact (World Bank, 2019). Mining's negative impact on biodiversity (Sonter et al., 2020) and its use of increasingly scarce freshwater resources (Tost et al., 2018) are also well documented.

Given these challenges, if a genuine attempt is to be made to deliver the required raw materials for the energy transition while mitigating a significant increase in negative societal and environmental impacts from increased mining activities, there is a clear need for a paradigm shift in the way mineral production systems operate. This means the prevailing mineral extraction techniques, mine site management practices and the mining sector's role within the economies of its host regions must be questioned and rethought.

Over the past two decades, the concept of the circular economy (CE) has emerged as a promising approach to transition industrial production and consumption systems towards higher levels of sustainability. It proposes a shift from the linear *take-make-waste* model to a regenerative system that prioritises material efficiency and minimises waste (de Jesus and Mendonça, 2018; Ellen MacArthur Foundation, 2012). The CE aims to "slow, narrow and close socioeconomic material cycles by retaining value as long as possible, thereby minimizing primary resource use, waste and emissions" (Haas et al., 2020, p. 1). As a framework for sustainable production, the CE concept has gained traction among scholars, policymakers, and the private sector, offering a new approach to view sustainability transitions.

Despite its growing popularity, the CE concept has also been critically received by a range of scholars (Corvellec et al., 2022; Kirchherr and van Santen, 2019) and its study has been complicated by a lack of a common definition and frameworks (Kirchherr et al., 2023). In addition, research on the CE and the application of CE thinking to date exhibits limitations in scope, as it does not equally encompass all aspects of global value chains and economic activities. In particular, there are two critical areas that are arguably underrepresented in the existing body of conceptual contributions and empirical studies on the CE. Firstly, the CE literature has predominantly focused on a limited subset of geographic contexts, particularly advanced industrial nations that consume rather than produce raw materials (Merli et al., 2018). Secondly, most empirical case studies have been confined to industries and industrial activities situated in the mid- and downstream segments of global value chains (Ragossnig and Schneider, 2019; Schöggl et al., 2020).

As a result, our understanding of what drives the successful implementation of CE approaches was primarily developed in the context of highly industrialised economies and industries operating in the mid- and downstream of global value chains, and is therefore largely based on empirical examples characterised by substantial territorial development, high levels of industrialisation, established industrial clusters, and regional economies with significant material consumption and stocks. However, the geographic and economic context of industries situated in the upstream segments of global value chains and their host regions, which often continue to rely on the extraction of raw materials, is significantly different.

On the one hand, the geographic contexts in which mineral extraction activities occur exhibit different spatial configurations of economic activity than those observed in mature industrialised countries. Regions with a heavy dependence on extractive industries are often characterised by enclave economies (Phelps et al., 2015), an outflow of raw materials to more industrialised regions (Haas et al., 2023), a comparatively low anthropogenic stock of

secondary materials (Maung et al., 2017), and an accumulation of large amounts of extractive processing waste (Hamraoui et al., 2024).

On the other hand, the upstream segments of global metals value chains face distinct operational challenges that set them apart from downstream industries in implementing CE approaches. Mining operations inherently deal with raw materials containing substantial impurities, making their processing more complex and less efficient than downstream manufacturing processes (Kalisz et al., 2022). Moreover, recent evidence demonstrates that the effectiveness and practicality of implementing CE approaches are significantly influenced by a company's position within the value chain and its established business model (Reike et al., 2018). In the case of mining operations, their upstream position and material-intensive business model create unique constraints and opportunities that differ markedly from those encountered by downstream industries in implementing CE approaches (Cisternas et al., 2022).

As a result, the current academic discourse on the CE arguably offers limited guidance to scholars and practitioners interested in applying CE approaches in upstream value chain segments that will play a crucial role in providing the critical minerals required for the energy transition. Given the growing consensus on the need for continued extraction of primary minerals to facilitate the energy transition, this thesis argues that the scholarship of the CE needs to pay more attention to raw material extraction activities.

In recent years, resource governance and responsible mineral sourcing have garnered renewed attention in the academic discourse (Dominish et al., 2019; Sovacool et al., 2020; Watari et al., 2021a). Despite the significance of these debates, the historical shortcomings of the mining industry in extracting materials responsibly and benefiting host countries and communities (Lèbre et al., 2020) have meant that they often occur in isolation from the scholarship and policy efforts focused on CE approaches. This thesis argues that this separation

represents a missed opportunity, as the CE paradigm offers an essential and highly relevant approach for fostering sustainable production and consumption practices, and novel business models across industries, value chain segments and differing geographic contexts. This perspective is crucial for policymakers and industry stakeholders who are seeking effective approaches to reduce the environmental footprint of mining activities while securing the materials necessary for a global energy transition.

The following section will elaborate on the specific aims and research questions that guide this investigation, further detailing this research's academic and practical contributions.

1.2. Significance, aims and research questions

This thesis explores the limitations of our existing understanding and approaches to CE transitions concerning primary critical energy transition minerals production. It is positioned as a critical examination of how our society obtains materials for its technological advancement and of the impacts of the energy transition's material intensity. Large-scale mining activities underpin both our current material needs and the anticipated mineral demands of the energy transition, making this examination essential.

Mining is an inherently place-based activity, as resource extraction can only occur where mineral deposits are located, adding a critical spatial dimension to this research problem (Bathelt and Glückler, 2005; Bridge, 2008, 2004). Moreover, large-scale mining activities – more than many other industries – are distinctly influenced by structural conditions, as they require substantial capital investments, lengthy permitting and construction processes, and have operational lifespans that often extend several decades (Born et al., 2023). These place-specific and structural characteristics mean that the mining industry and regions hosting extractive activities often exhibit distinctive contextual factors (McElroy, 2018).

Using a *critical realist* approach, with its emphasis on exploring the deeper, often hidden, structural mechanisms that influence observable phenomena, this thesis aims to dissect the complexities and distinctive context of circular economy transitions within mineral resource extraction systems and the interplay between material realities and societal structures. In particular, it asks the following two overarching research questions:

(1) *What is the mining sector's role in the transition towards a more circular economy?*

(2) *What place-specific mechanisms and structural conditions enable or inhibit circular economy transitions in the mining sector and its host regions?*

As such, this thesis's aim is not only to explore the role that the mining sector will need to play in transitioning towards more circular modes of production and consumption but also to identify how CE approaches can be applied to the mining industry. Moreover, this project aims to challenge the existing techno-economic paradigms of *sustainable mining* by highlighting the need to use a system-based approach[1] to mitigate the adverse effects of mining, such as biodiversity loss, land degradation, water overconsumption, and unequal development.

However, the research goes beyond merely applying the CE paradigm to the mining sector. Instead, it leverages the case of the mining industry to apply existing economic geography theory to the study of the circular economy to offer new perspectives on the role of place-based factors in shaping circular economy transitions. This provides a more nuanced understanding of the challenges and opportunities for implementing CE approaches in different geographical contexts. As such, the themes explored across the different chapters and papers connect the practical challenges of applying CE approaches in the mining sector and its host

[1] A systems-based approach is a holistic methodology that views complex phenomena as interconnected systems rather than isolated components (Bertalanffy, 1973). This approach emphasises the relationships, interactions, and interdependencies between various elements within a system (Checkland, 1981). It focuses on understanding the dynamic relationships between elements and how these relationships contribute to emergent properties and behaviours that cannot be predicted from studying individual parts alone (Goldstein, 1999; Holtz et al., 2015).

regions with broader economic geographical and sustainability transition theories, providing a cohesive narrative that underscores the complexity of transitioning toward material-efficient, net-zero carbon economies globally.

To deliver on these aims, the following more detailed practical research questions (RQs) were identified:

RQ1: How does the forecasted demand for critical energy transition minerals impact the ambition of transitioning to a circular economy?

RQ 2: What are the limitations of downstream CE strategies (e.g. recycling) for critical energy transition minerals sourcing?

RQ 3: What is the existing understanding of the role of critical energy transition minerals' extraction in a circular economy?

RQ 4: What role can CE strategies and practices play in making primary mineral extraction processes more responsible?

RQ 5: How can CE principles, strategies and practices be integrated into primary mineral extraction processes?

RQ 6: What are the barriers and enablers for CE transitions in mineral resource-dependent regions?

RQ 7: How does the spatial configuration of economic activity in mineral resource-dependent regions affect their ability to transition towards a more circular regional industrial ecosystem?

By asking these questions, this thesis seeks to contribute both theoretically and practically to discourses on sustainable mining, the responsible sourcing of minerals critical for the energy transition, circular economy transitions, and the economic geography of extractive industries, while also offering a compelling case for why scholars should invest in deeper, more context-sensitive investigations into the spatial dynamics of circular economy transitions and sustainable primary material extraction. Firstly, it explores how CE approaches can contribute to energy and sustainability transitions, as well as to meeting overall material demand for the energy transition. Secondly, through a single case study of Chile's mining regions, it provides novel insights into the spatial dimensions of CE transitions in the context

of resource-dependent regions and the application of CE approaches in large-scale copper and lithium mining. Thereby, the thesis aims to provide valuable insights into how CE transitions might reshape economic activities and potentially contribute to more equitable and sustainable forms of natural resource exploitation and regional development in resource-dependent regions.

1.3. Thesis structure and overview

This thesis is article-based and is centred around three distinct research papers that have all been published in peer-reviewed journals. The first article (Chapter 4) was published in *Resources, Conservation and Recycling* in November 2023, while versions of the other two articles (Chapters 5 and 6) were published in *Resources Policy* and *Progress in Economic Geography,* respectively, in March and April 2025. This thesis consists of seven chapters, divided into two parts: Part I (Chapters 1-3) positions the research project, while Part II (Chapters 4-7) presents this project's empirical research.

1.3.1. Part I: Positioning the research project

Chapter 1: Introduction

This introductory chapter provides the broader context for this research. It highlights the complex interplay between resource extraction, environmental sustainability, and the energy transition, focusing on the urgent need for re-imagining extractive production processes. The chapter emphasises the importance of increasing our understanding of how CE approaches can be adapted to mining contexts, underscoring that the prevailing *linear* resource extraction models cannot support a decarbonised future while addressing growing concern over negative environmental and social impacts of large-scale mining activities. The chapter also explains the aim and objectives of this thesis, discusses why this study is important and states the overall aims of the research, before briefly summarising the seven chapters.

Chapter 2: Literature review

Chapter 2 provides a comprehensive review of the key topics of the thesis, highlighting gaps in the literature and setting a background for the subsequent chapters. It brings together relevant aspects of the emerging field of circular economy, as well as literature on sustainable mining practices, sustainability transitions research and economic geography. The chapter is divided into two main parts.

The first part establishes the significance and relevance of this thesis' investigation and how the lack of understanding of CE adoption in the mining sector emerged as a critical research problem. It begins by examining the material foundations of the energy transition, highlighting the growing demand for critical energy transition minerals and the associated environmental and social challenges. The chapter also explores the limitations of current approaches to meeting this demand, including the constraints of end-of-life (EoL) recycling and other downstream CE strategies, before tracing the evolution of the scholarly enquiry into the circular economy.

The second part of the chapter outlines the analytical framework that underpins this research. It draws on key concepts and ideas from economic geography and sustainability transitions research, which serve as the foundation for understanding the complex and multi-dimensional dynamics involved in implementing CE approaches in the mining sector and its host regions. This analytical approach to the literature review is crucial, as there has been limited application of the CE concept to mining or other upstream industries in the past, resulting in a limited foundation for determining how practitioners interpret and utilise the concept in this context. By synthesising insights from the intersecting but distinct fields of circular economy research, economic geography, and sustainability transition studies, this chapter provides a novel perspective on the challenges and opportunities for applying CE approaches in the mining sector. The chapter concludes by identifying key research gaps. These

gaps form the basis for the research questions that the subsequent empirical chapters will address.

Chapter 3: Research design and methods

Chapter 3 outlines the methodological approach and research design employed in this thesis. It introduces the project's underlying ontology and epistemology before explaining the rationale behind the chosen methods and how they align with the research objectives. Moreover, it discusses the reflexive research approach I adopted in this project and how my background and positionality shaped the research process and its outcomes. Finally, the chapter details the data collection processes and analytical techniques that underpin the research, before addressing the limitations of the chosen methodological approach and how I attempted to mitigate them.

1.3.2. Part II: Empirical research

The empirical section of this thesis comprises three articles submitted for publication in peer-reviewed journals and a chapter that gathers the conclusions drawn throughout the research project. Although all three articles explore the role of the mining sector in a circular economy and the adoption of CE principles, strategies and practices in the mining sector and its host regions, each employs distinct methodologies, draws on different theoretical frameworks, and engages with different yet interconnected academic audiences.

Chapter 4: The limitations of end-of-life copper recycling and its implications for the circular economy of metals

Chapter 4 examines the notion that recycling and reuse, terms often used synonymously with the circular economy, are not a comprehensive solution to society's future material demands. It does this by investigating the limitations of the current focus of academic enquiry and policy efforts on EoL recycling strategies. To evaluate how EoL recycling strategies could meet future metal demand and replace primary production, it presents a novel dynamic probabilistic

material flow analysis (MFA) model, developed and tested on copper, a key critical energy transition mineral. The chapter also provides a detailed analysis of the modelling results and discusses the implications of the findings.

It concludes by arguing that there is a pressing need for alternative CE strategies to EoL recycling, such as mitigating the harmful impacts of primary metal production through adopting CE approaches in the mining sector. It, therefore, highlights the importance of taking a broader approach to circularity and directing research efforts toward pathways for integrating CE thinking into industrial mining production systems. Finally, it positions one of the core questions of this thesis: higher levels of circularity in downstream value chain segments will not remove the need for primary production and extraction of minerals in the short- to medium-term, but can adopting CE principles, strategies and practices in industrial mineral production systems reduce some of the negative externalities of large-scale mining?

Chapter 5: Application of circular economy approaches in the mining sector: evidence from Chile

Chapter 5 attempts to answer this question by investigating the current state of CE implementation in the mining sector and the potential of CE approaches to tackle some of the sector's sustainability challenges. It begins by examining the conceptual limitations of the CE literature in guiding the application of CE approaches in the mining sector. In this chapter, I argue that current conceptual frameworks to study the circular economy lack applicability to mining and other upstream industries. Based on 31 individual semi-structured and 11 focus group interviews with 54 experts from industry, policy, and academia, I identify three new conceptual elements that enable a system-level analysis of CE implementation tailored to the context of the mining industry.

This new conceptual approach is then applied to the case of Chile, where I map existing CE approaches deployed in the mining sector before discussing the challenges that the mining sector faces in applying CE approaches at scale.

Chapter 6: Exploring the spatial dynamics of circular economy transitions: insights and lessons from Chile's mining territories

Chapter 6 investigates the spatial dynamics of CE transitions in mineral resource-dependent regions. It examines the role of space and the spatial configuration of economic activity as critical factors that enable the application of CE approaches. Using Chile's mining territories as a case study, the paper explores how the unique configuration of economic activities in regions that host mining activities influences their ability to transition towards a more circular regional industrial ecosystem. These regions are often characterised by economic enclavism and weak local linkages, which shape their ability to transition towards more circular modes of production and consumption. Through 23 semi-structured and five focus group interviews with industry leaders, policymakers, and academics, the study identifies three distinct spatial dimensions that impact the ability of economic actors in resource-dependent regions to implement CE approaches.

Finally, the chapter also reflects on the current state of economic geographic enquiry into the CE concept and the need to more deeply incorporate geographic considerations into the study of both the dynamics of CE transitions and sustainability transitions more broadly. The paper concludes by arguing that overcoming the spatial and institutional barriers inherent in enclave economies is essential for fostering sustainable regional industrial ecosystems and advancing CE transitions in resource-dependent regions.

Chapter 7: Conclusion

The final chapter synthesises the key findings from the three empirical papers and discusses their implications for theory and practice. It reflects on the contributions of the thesis to the fields of circular economy, economic geography and sustainability transitions research. The chapter also identifies the limitations of the research and suggests directions for future study before giving some final remarks.

2. Literature review

This chapter will provide a comprehensive review of the academic literature relevant to this research project. As such, it sets the stage for the thesis by identifying gaps in the existing literature and establishing the theoretical foundation for this project. Given the limited application of the CE concept to mining or resource-dependent regions in the past and the lack of a research tradition to build upon for determining how practitioners interpret and apply the CE concept in this context, this literature review is structured into two distinct parts. The first part establishes the importance of studying the application of circular economy thinking to the mining sector and resource-dependent regions. In contrast, the second part provides a theoretical foundation and analytical lens for studying the dynamics of CE adoption in this context.

Consequently, the first part of this literature review examines why the implementation of CE approaches in the mining sector and resource-dependent regions presents a critical research problem. It explores the material foundations of the energy transition, highlighting the growing demand for critical energy transition minerals and associated sustainability challenges. This section also critiques current approaches to meeting this demand, including recycling and other downstream CE strategies. Finally, it traces the evolution of the scholarly enquiry into

the circular economy, critically examines existing CE frameworks[2], and identifies their limitations when applied to primary resource extraction.

The second part of the literature review outlines the analytical framework that underpins this research. It draws on key concepts and ideas from economic geography and sustainability transitions research, which serve as the foundation for this project's understanding of the complex and multi-dimensional dynamics involved in implementing CE approaches in the mining sector and its host regions.

The choice to approach this research through the lens of economic geography and sustainability transitions research is deliberate and significant. Both offer valuable frameworks for exploring CE implementation in the mining sector and its host regions, as they present an analytical lens that recognises the unique spatial characteristics that shape economic outcomes (Duranton and Kerr, 2018; Geels, 2002; Gertler, 2018). As the remainder of this chapter will explore in more depth, mining operations are inherently tied to specific geographic locations and create particular configurations of economic linkages within their host regions. Similarly, resource-dependent regions often exhibit specific spatial factors different from other regions and territories (McElroy, 2018). These characteristics necessitate a tailored approach to CE that considers the sector's and its host regions' distinctive features.

These unique characteristics of the mining sector have significant implications for the applicability of the current conceptualisation of the circular economy and the implementation of CE approaches. While much of the existing CE literature focuses on strategies applicable to diversified, industrialised economies with substantial material stocks and established industrial clusters, resource-dependent regions and the extractive industries located in them arguably

[2] Circular Economy (CE) frameworks refer to the conceptual models and analytical tools developed to guide and assess transitions from linear "take–make–waste" systems towards more circular modes of production and consumption. They typically organise strategies for reducing resource extraction, extending product lifecycles, and minimising waste and provide principles or typologies for applying circularity at different scales — from products and firms to value chains, industrial systems, and territories.

require a different approach. The economic geography and sustainability transitions perspective enables this project to examine how the spatial distribution of economic activities, the flow of resources, and institutional structures in these regions influence the potential for and challenges to CE implementation.

Given these unique characteristics of the mining sector, developing a nuanced understanding of how CE approaches can be effectively applied to mineral extraction activities is crucial. This necessitates a deeper exploration of the sector's specific context and the potential pathways for integrating CE approaches into mining operations. To lay a foundation for this exploration, the following section will delve into the material foundations of the energy transition, examining the growing demand for critical energy transition minerals and the associated sustainability challenges.

2.1. The material foundations of the energy transition

The importance of intangible capital, assets with no physical or financial embodiment, such as intellectual property and digital services, has increased significantly over the last few decades (Corrado et al., 2016). At the same time, the perceived importance of what journalist and author Ed Conway (2023) calls the *material world* – the network of physical resources and materials that underpin modern civilisation - has diminished significantly within the academic and policy discourse over the past decades. Conway argues that while we often perceive our lives as increasingly *ethereal* – driven by digital information and services – our existence remains deeply anchored in tangible, extracted materials like iron, copper, and lithium. These materials are fundamental to the infrastructure of everyday life, powering everything from transportation to technology.

2.1.1. Emerging supply challenges for critical energy transition minerals

One area where the continued importance of the *material world* is acutely felt is in discussions about the material needs for the global energy transition. Minerals such as copper, lithium, nickel, and cobalt are essential for various clean energy technologies, including wind turbines, solar panels, electric vehicles, and electricity transmission infrastructure. There is now growing evidence that the significantly higher material intensity of clean energy technologies, compared to fossil fuel-based technologies, as well as growing populations and rising incomes, are likely to increase the demand for these so-called *critical energy transition minerals* rapidly and continuously until at least 2050 (Hund et al., 2020; IEA, 2021; Seck et al., 2020; Simas et al., 2022; Watari et al., 2019). Although material demand forecasts are highly uncertain, there is a growing consensus that the demand for all major metals will grow significantly. For instance, Watari et al. (2020) reviewed 70 studies forecasting metal demand. They find that demand for all major metals is likely to increase continuously until 2050, with the demand for aluminium (215 %), copper (140 %), nickel (140 %) and iron (86 %) forecasted to grow significantly relative to demand in 2010. This means that to meet the ambitious climate targets set out in the Paris Accord, the supply of critical energy transition minerals will need to rise rapidly over the coming three decades.

Despite strong evidence of the impending demand increases of critical energy transition minerals, the broader academic and policy discourse paid limited attention to the material aspects of the energy transition in the years following the signing of the Paris Accord. This has changed recently. Not only are there growing numbers of academic publications that discuss the importance of paying attention to the material aspects of the energy transition (e.g. Hammond and Brady, 2022; Nature, 2023; Srivastava and Kumar, 2022), but there is also growing policy attention through initiatives such as the *United Nations Secretary-General's Panel on Critical Energy Transition Minerals* (UN, 2024), the enactment of the European

Union's *Critical Raw Materials Act* (European Parliament, 2024) and the establishment of the *Minerals Security Partnership*.

One key focus of this discourse is the significant environmental and social challenges that increased mining activities – if not managed appropriately – could bring to regions where mining activities are concentrated. This is underpinned by a growing understanding that the extraction and processing of metals often entail substantial ecological and societal trade-offs, which must be carefully managed to avoid undermining the very sustainability goals that the energy transition seeks to achieve. This discussion is particularly pertinent as mining activities' environmental, social and economic impacts have historically surpassed those of other industrial activities in scale and severity, affecting various aspects of the environment and society.

2.1.2. Environmental and social impacts of mineral extraction

One of the most pressing sustainability challenges associated with mining is the enormous volume of waste it generates. The global mining industry is recognised as the world's foremost waste producer by volume. Estimates indicate that the annual generation of solid waste from the primary production of mineral and metal commodities surpasses 100 billion tonnes (Tayebi-Khorami et al., 2019). In metal mining, the targeted minerals represent only a small fraction of the volume of material excavated and processed to extract the target metal. Thus, the vast majority of the mined material ends up as waste rock or tailings[3]. To make this more tangible, a recent analysis by the International Energy Agency (IEA) (2021) shows that nearly 700 tonnes of waste rock and tailings were generated to produce a single tonne of copper or nickel.

[3] Tailings are the waste materials left after the target mineral is extracted from the ore. The majority of tailings material is disposed of in a liquid or semi-liquid form.

This figure represents a 30 per cent increase since 2010, a trend that is forecasted to continue, driven by declining ore quality and the increasing prevalence of surface mining (IEA, 2021).

The global production of mine tailings, in particular, has been increasing significantly, with recent estimates suggesting an annual output of approximately 14 billion tonnes, the equivalent of 5.6 million Olympic-sized swimming pools (Adiansyah et al., 2015). The management of these vast quantities of mine waste requires extensive land use, immobilises substantial amounts of process water, and poses significant environmental and safety risks (Wang et al., 2014). Over time, numerous incidents involving collapses of tailings storage facilities and catastrophic tailings releases have occurred, highlighting the potential for severe environmental disasters.

However, the environmental footprint of mining extends far beyond waste generation. Land use changes associated with mining activities can lead to significant habitat destruction and fragmentation (Maus et al., 2022). Mining operations significantly alter landscapes and contribute to deforestation. From 2001 to 2020, mining and related activities were responsible for the loss of nearly 1.4 million hectares of trees globally. While mining's contribution to global tree cover loss is relatively small compared to other drivers, its regional impacts can be disproportionately large (Stanimirova et al., 2024). The impact on water resources is also substantial, with mining activities altering the natural flow of groundwater and potentially harming increasingly scarce freshwater systems in certain regions (Lakshman, 2024; Meißner, 2021). Moreover, the contamination of water resources by heavy metals and toxic chemicals from mining waste poses significant risks to human health and agricultural land use (Tost et al., 2018).

The primary production of minerals and metals also significantly contributes to global greenhouse gas emissions. It is estimated that mining and metals processing accounted for

approximately 10 per cent of total global energy-related GHG emissions, a figure that continues to rise (Azadi et al., 2020; Greene, 2017). Mining operations can also have severe impacts on biodiversity, particularly when they occur in ecologically sensitive areas. The direct destruction of habitats and indirect effects such as pollution and ecosystem fragmentation can lead to significant biodiversity loss (Sonter et al., 2020). Furthermore, mining activities often disproportionately affect Indigenous communities, leading to displacement, loss of traditional livelihoods, and cultural disruption. The encroachment of mining operations on Indigenous lands has been a source of ongoing conflict and social injustice in many parts of the world (Lèbre et al., 2020; Owen et al., 2023).

2.1.3. Economic impacts of mineral extraction

In addition to the environmental and social impacts of mining, extractive activities also have significant implications for the development of territorial and regional economies. One widely discussed perspective in the literature is the so-called resource curse hypothesis. The resource curse hypothesis posits that countries face long-term trade-offs when choosing to extract natural resources, such as minerals, oil, and gas, at the expense of potentially more sustainable economic alternatives like manufacturing, agriculture, or service industries (Collier and Hoeffler, 2005; Sachs and Warner, 2001). According to orthodox interpretations of this hypothesis, the curse manifests as countries become increasingly dependent on resource revenues. The curse can manifest itself in various forms, including economic instability, reduced investment in human capital, and increased vulnerability to external market fluctuations (Auty, 2017). Although the empirical evidence for the existence of the resource curse has weakened since the original formulation of the hypothesis in the early 2000s, the dependence on natural resources can negatively impact a nation's long-term prospects for more evenly distributed economic growth (Owen et al., 2021; van der Ploeg and Poelhekke, 2009).

In addition to country-level impacts of an overly strong reliance on extractive activities, core-periphery dynamics further complicate the economic development pathways of resource-rich regions. These regions often lie in the periphery of economic and political power centres, leading to extractive relationships that benefit the core at the expense of the periphery (Pugh and Dubois, 2021). The challenge for peripheral regions lies in retaining the benefits of their resource endowments rather than perpetuating historical trends of resource extraction that primarily benefit distant economic centres (Hayter et al., 2003; McElroy, 2018).

Evidence suggests that many resource-dependent regions are unable to overcome this challenge. For instance, Lashitew et al. (2021) find that territories characterised by export-oriented, specialised production of natural resources often display lower levels of local economic integration than territories without natural resource extraction. This lack of integration results in fewer local synergies, reduced economies of scale effects, and limited knowledge spillovers compared to more integrated industrial ecosystems (Buur et al., 2013). As a result, many resource-rich regions develop into what is known as *economic enclaves* or simply *enclaves*. Phelps et al. (2015, p. 3) define economic enclaves as "physically, administratively, or legally bounded territory whose geography or morphology is intimately related to the following economic characteristics: dependence on one or a few large firms; high specialization in one activity; and weak integration into the local economy, which is used primarily to access some local factors of production." This enclave structure can disconnect the mining industry and the broader regional economy, limiting the potential for sustainable, diversified economic development (Arias et al., 2014).

To sum up, the growing demand for energy transition minerals, coupled with the significant environmental, social, and economic challenges associated with their extraction, presents a complex dilemma for policymakers and industry stakeholders. As the world strives to meet ambitious climate targets, it must simultaneously address the sustainability concerns

of increased mining activities. The recognition of this challenge has created a lively discourse on how the negative impacts of resource extraction can be mitigated without hindering the global energy transition. One proposed solution approach prominently featured in this discourse that is gaining increasing traction in academic literature and policy discussions is the circular economy (CE) concept.

The following sub-section will explore the roots and current literature on the CE concept before discussing its limitations concerning application to the challenges of providing sufficient quantities of critical energy transition minerals responsibly and sustainably.

2.2. The circular economy of critical energy transition minerals

This section will examine the historical development of CE thinking, review critical theoretical frameworks and models, and analyse recent empirical studies on CE adoption across different industries and regions.

2.2.1. Conceptual origins and evolution of the circular economy

Proponents of the circular economy advocate for shifting our economic system from the existing linear *take-make-waste* economic model that leads to significant material inefficiencies and excessive material consumption to a regenerative system that prioritises material efficiency and minimises waste by circulating materials at their highest value for as long as possible (de Jesus and Mendonça, 2018; Ellen MacArthur Foundation, 2012). As such, the CE can be seen as an *umbrella concept* that promotes a wide range of waste and resource management strategies with an emphasis on extending the productive life of resources to achieve more sustainable economic outcomes (Blomsma and Brennan, 2017; Pauliuk, 2018).

Instead of introducing an entirely new approach to waste and resource management, the CE concept provides a fresh perspective on ideas to changing the system of production and consumption that various scientific disciplines have advocated since the 1960s (Boulding,

1966; Meadows et al., 1972). By highlighting the potential of combinations of existing approaches to extend resource use, the CE concept "constructs and legitimises a space for the interrogation of the appropriate and effective use of such strategies" (Blomsma, 2018, p. 969).

Many scholars see the starting point of CE scholarship in Pearce and Turner's (1990) seminal work *Economics of Natural Resources and the Environment*, which brought together concepts from different intellectual traditions and popularised the concept of the circular economy. Around the same time, other conceptual approaches to more sustainable resource management, such as *industrial symbiosis* (e.g. Ayres and Simonis, 1994; Boons et al., 2011; Chertow, 2007) and *industrial ecology* (e.g. Ayres and Ayres, 2002; Ehrenfeld, 2000; Erkman, 1997; Frosch, 1992; Socolow, 1994; van Berkel et al., 1997) attempted to learn from the efficient resource recycling observed in natural systems and apply them to industrial production systems.

In the wake of the growth of these new approaches that questioned the sustainability of existing industrial systems, the CE concept began to receive significant scholarly attention from the late 1990s onwards (Blomsma and Brennan, 2017; Ghisellini et al., 2016). In the early days of CE scholarship, its focus was predominantly on waste management, industrial ecology and industrial symbiosis, focusing on reducing waste and improving resource efficiency in industrial processes. As the field developed, scholars increasingly began examining broader topics and changes to economic and business models required to achieve higher levels of circularity. This included research topics such as sustainable waste management (Greyson, 2007; Liu et al., 2009), cradle-to-cradle approaches (Braungart et al., 2007; Braungart and McDonough, 2009; McDonough and Braungart, 2013), research on circular business models (Bocken et al., 2014) and product-service systems (Tukker, 2015; Tukker and Tischner, 2006), as well as strategies for extending product lifespans through reuse, repair, recycling and remanufacturing (Allwood, 2014; Rashid et al., 2013). There was also growing interest in how

the CE concept could be applied at different scales - from individual products and companies to entire economic sectors and regions (Ghisellini et al., 2016).

By the early 2000s, the CE concept also began to gain traction among policymakers. In 2002 the Chinese government passed the *Cleaner Production and Promotion Law* (People's Republic of China, 2002), which was followed by the *Circular Economy Promotion Law* in 2009 (People's Republic of China, 2009). The EU followed suit a few years later, and the CE concept and its associated strategies became the foundation for the *EU Action Plan for the Circular Economy* (European Commission, 2015). A growing number of companies have also started incorporating the CE concept into their corporate strategies, with an extensive range of companies increasingly adopting language and sustainability commitments referencing the concept (Opferkuch et al., 2021; Stewart and Niero, 2018). However, many of these commitments have been found to remain aspirational (Jones and Comfort, 2017).

Public and private organisations' increasing interest in the CE concept has shifted the academic discourse. Growing numbers of academic papers are now not only exploring the theoretical underpinnings of the concept but are also increasingly conducting empirical studies on the implementation and adoption of CE principles, strategies, and practices (Merli et al., 2018). Moreover, there is an increased interest in the role of policy in driving CE transitions (Kirchherr et al., 2018). As a result of these developments, there has been an explosion in the range of topics studied under the umbrella of the CE. The topics range from cleaner production (Geng et al., 2012; Hong and Li, 2013), resource efficiency (Ekins et al., 2016), closed-loop supply chains (Gupta and Palsule-Desai, 2011; Ji et al., 2014; Mirhedayatian et al., 2014) and the interaction of sustainable consumption and production (Swain and Sweet, 2021) to consumer acceptance of circular products and services (Camacho-Otero et al., 2018) to name but a few of the most influential. Interdisciplinary approaches are also becoming more common, integrating perspectives from engineering, business, environmental science, and

social sciences, reflecting the complex, systemic nature of the CE concept and the need for holistic solutions that address technical, economic, and social aspects of a CE transition (Geissdoerfer et al., 2017). This interest has continued unabatedly, with more academic papers and grey literature on the CE being published every year (de Jesus and Mendonça, 2018; Kirchherr et al., 2023, 2017; Lieder and Rashid, 2016).

As the CE concept gained traction in academic and policy circles, its application to the metals and mining sector also began to receive increased attention (Kalmykova et al., 2018; Merli et al., 2018). This is not surprising, as many minerals and metals, unlike carbon-based raw materials, do not lose their intrinsic properties during recycling and can be re-used multiple times without losing their quality or functionality (Hagelüken et al., 2016). Moreover, scholars are increasingly recognising metals' critical role in modern economies and the potential for circular approaches to address the environmental and social challenges associated with their extraction and use (e.g. Haas et al., 2023; Hagelüken and Goldmann, 2022; Jackson et al., 2014; Reuter et al., 2019).

Early research in this area focused primarily on improving recycling rates and developing more efficient recovery processes for metals from end-of-life (EoL) products (Graedel et al., 2011; Reck and Graedel, 2012; Reuter et al., 2013). These studies highlighted the technical feasibility of recovering a wide range of metals from various waste streams but also identified significant challenges related to product design, collection systems, and the economics of recycling. As the field matured, researchers began to explore more comprehensive CE strategies for metals beyond recycling. This included investigations into the potential for remanufacturing and refurbishment of metal-intensive products (Cimprich et al., 2023; Jackson et al., 2014), as well as the development of new business models that could extend the lifespan of metal-containing products through sharing, leasing, and product-service systems (Bocken et al., 2014; Reuter et al., 2019; Tukker, 2015).

2.2.2. Challenges and limitations of existing circular economy approaches for critical energy transition minerals

Despite the significant traction that the CE concept has gained in recent years as a potential solution to the environmental and social challenges associated with resource extraction and consumption, the concept still faces various issues regarding its application to critical energy transition minerals.

As the field matured, scholars moved beyond theoretical discussions to explore the practical implications and transition dynamics of implementing CE approaches (e.g. Cantú et al., 2021; Cimprich et al., 2023; Cisternas et al., 2022; Greer et al., 2022; Kalmykova et al., 2018; Kulczycka et al., 2020; Rizos et al., 2021). This shift in focus has led to a proliferation of frameworks that attempt to conceptualise the pathways to operationalise the CE through various strategies for cascading, looping, or cycling resources and waste (Blomsma and Brennan, 2017; Ekins et al., 2020). These CE frameworks act as conceptual models that frame our understanding of what a circular economy could look like (Blomsma, 2018). Some of the most prominent frameworks include the Butterfly diagram and the ReSOLVE framework (EMF, 2013, 2012), Cradle-to-Cradle™ (Braungart and McDonough, 2009; McDonough and Braungart, 2013), the Waste Hierarchy (European Commission, 2014, 2008), but also the Performance Economy (Stahel, 2010), Material Efficiency (Allwood, 2014; Allwood et al., 2011) and the Blue Economy (Pauli, 2010).[4]

These frameworks typically present a hierarchy of circular strategies, ranging from those that require minimal intervention (such as 'refuse' and 'reduce') to more resource-intensive options (like 'recycle' and 'recover') (see Figure 2.1). Each alternative can be referred to as a value retention option (RO) (Reike et al., 2018). The most common iterations include

[4] See Blomsma (2018) for an in-depth discussion of each of these frameworks.

the 3R (Reduce, Reuse, Recycle), 4R (adding 'Recover'), and more expansive versions such as the 9R framework, which incorporates strategies like 'Rethink', 'Refurbish', and 'Remanufacture' (Ekins et al., 2020; Reike et al., 2018). Thus, these frameworks provide a structured approach to evaluating and prioritising circular strategies (Blomsma and Brennan, 2017).

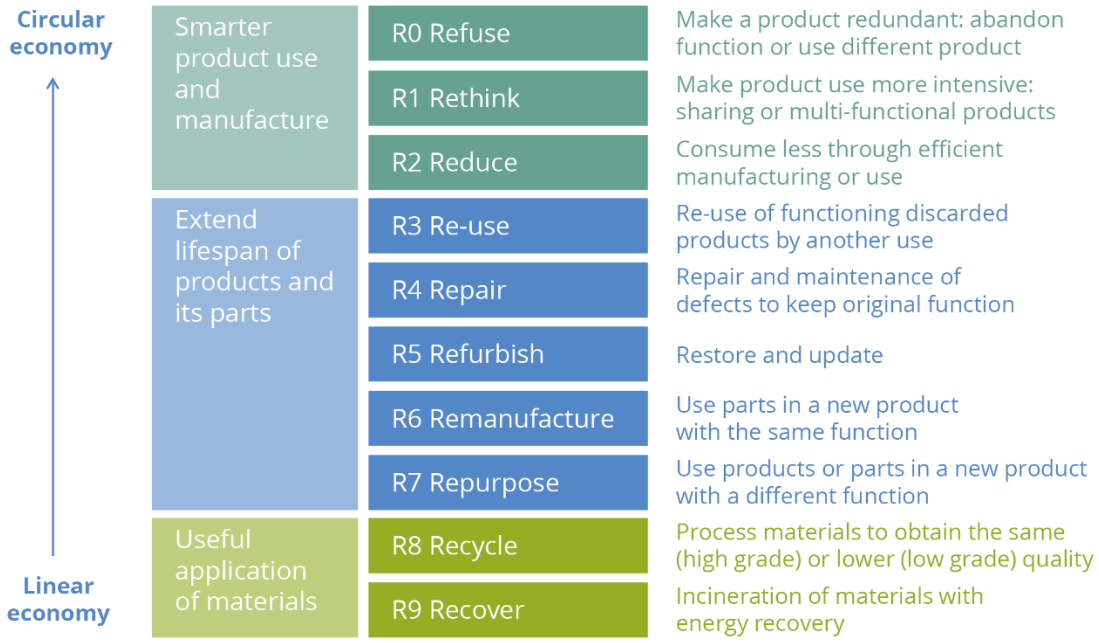


Figure 2.1 Typology of circular economy strategies. Source: Potting et al. (2017)

While these prominent frameworks have demonstrably shifted the perceived scope and purpose of waste and resource management, leading to the establishment of particular practices in industrial systems, they are not without their limitations (Boons, 2009; Corvellec and Hultman, 2012; Silva et al., 2016). In particular, the continued fuzziness and widespread disagreement on the definition of the CE, as well as disagreements regarding the ultimate goal of applying CE approaches, have resulted in each framework emphasising the importance of different CE strategies (Blomsma, 2018; Kirchherr et al., 2023). Consequently, each framework develops its particular vision of the importance of waste and resource management, identifies

different shortcomings in current practices, and suggests a unique combination of strategies for reducing the harm caused by inefficient and ineffective resource use.

Despite their differences, most CE frameworks claim broad applicability across various materials, scales, life cycle stages, and value chains (Ghisellini et al., 2016; Kalmykova et al., 2018; Kirchherr et al., 2017). However, this assertion of universal applicability masks several understudied areas in the CE literature. In particular, a critical examination reveals two critical areas that are arguably underrepresented in the existing body of conceptual contributions and empirical studies on the CE: (1) a strong focus on downstream value chain segments and (2) a geographical focus on raw material-consuming regions rather than raw material-producing regions. I will now discuss each of these in turn.

2.2.2.1. Narrow focus on downstream value chain segments

Firstly, much of the CE literature implicitly focuses on retaining the materials contained in fabricated products rather than holistically investigating how all value chain segments can contribute to higher levels of circularity. This has resulted in limited engagement with upstream value chain segments and the management of resources within industrial production processes that produce the raw materials used as inputs by downstream value chain segments (Kalmykova et al., 2018). As a result, many of the most prominent CE frameworks often conceptualise raw material production as a material flow outside the scope of intervention (see Figure 2.2).

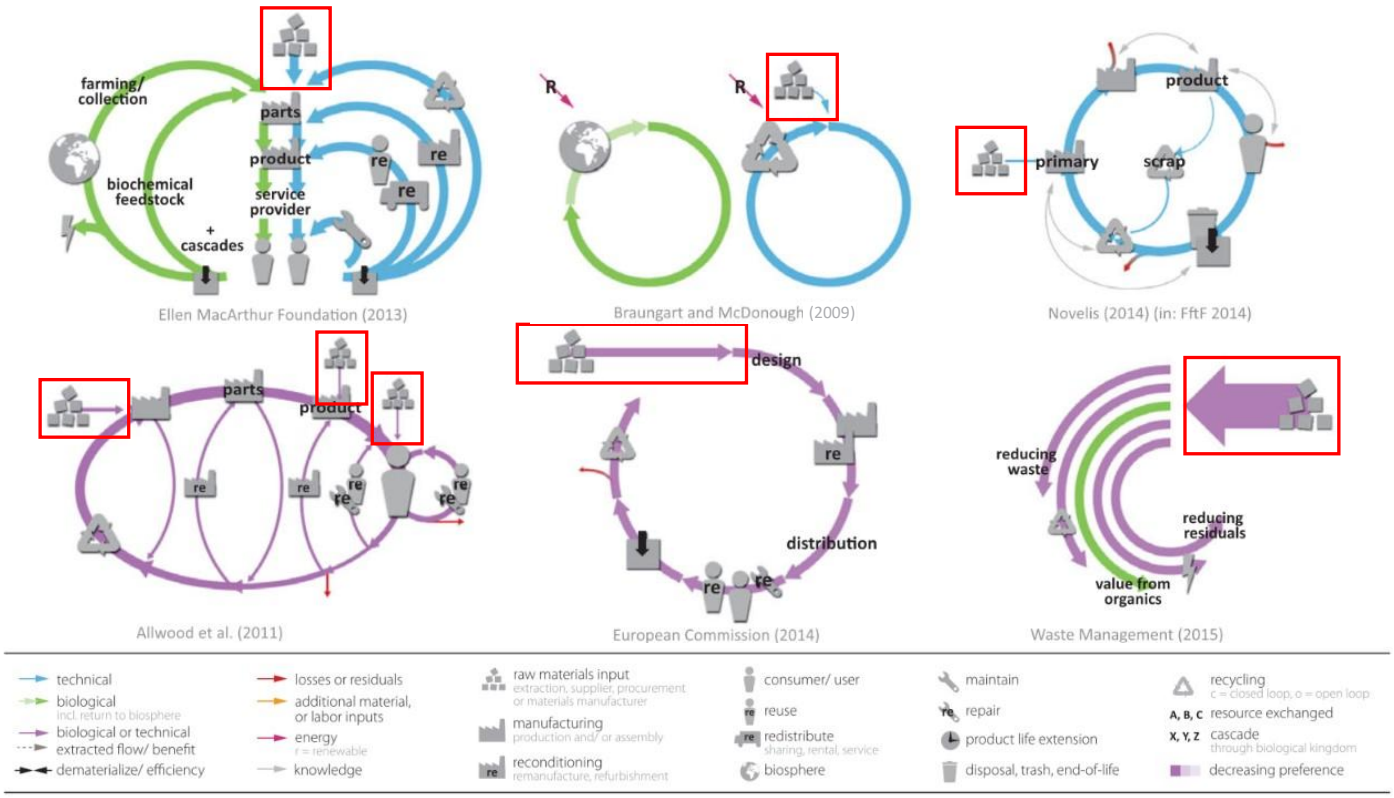


Figure 2.2: High-level overview of a selection of interpretations of circular economy frameworks adapted from Blomsma and Brennan (2017). The role of raw material inputs in each of the selected frameworks is highlighted in red.

Most research and policy efforts to develop and promote CE approaches to meet the growing demand for energy transition metals have predominately focused on interventions in downstream value chain segments (Watari et al., 2021a). In particular, the potential offered by recovering and recycling minerals and metals from previously discarded products that have reached their end-of-life (EoL), also known as secondary sources or *urban mines*, has received a large proportion of the attention (e.g. Ciacci et al., 2017; Cossu and Williams, 2015; Espinoza et al., 2020; Xavier et al., 2023). Similarly, researchers are increasingly exploring ways in which society can extend the lifecycle of products to lower the demand for minerals required to fabricate new products (e.g. Reike et al., 2018; Watari et al., 2021a). While evidence suggests that these downstream CE strategies are crucial in the attempt to reduce society's resource demands and achieve higher levels of circularity, there is a growing consensus in the literature that the majority of new supply to meet this growing demand will need to come from extracting

minerals from the earth's crust, also known as primary sources, for the foreseeable future (Bianchi and Cordella, 2023; Dong et al., 2019; Reuter et al., 2013; Simas et al., 2022; Valero et al., 2018).

There are several reasons for this. On the one hand, the existing stock of materials extracted and used previously that are available for reuse or recycling cannot match future demand. Many products that could act as secondary sources of metals remain in use for extended periods (Haas et al., 2015; Watari et al., 2021c). In addition, technological requirements for materials constantly evolve, leading to demand for materials that have not been accumulated in the anthroposphere in sufficient quantity previously (Langkau and Tercero Espinoza, 2018). As a result, the existing stocks of most mined raw materials are too small to cover the growing demand driven by rising incomes and emerging technologies (IEA, 2021; Watari et al., 2019). On the other hand, significant barriers remain in reducing the amount of metals lost during each usage cycle. In particular, both adapting existing waste management systems to increase the reuse and collection of EoL products containing valuable metals and decreasing significant material losses in the recycling process is proving difficult to achieve (Charpentier Poncelet et al., 2022; Reuter et al., 2019).

2.2.2.2 Geographic focus

Secondly, there is a strong geographic focus on resource-consuming countries in the empirical CE literature. Most empirical case studies in the CE literature are drawn from advanced industrialised nations (Merli et al., 2018). These regions are comparatively wealthier and predominantly consume rather than produce raw materials (United Nations Environment Programme, 2024). As these regions' economic activities are primarily positioned in the downstream segments of global value chains, CE approaches studied in these contexts have naturally concentrated on the downstream value chain stages concerned with the production and EoL management of final products (Kalmykova et al., 2018). This downstream focus is

further shaped by the fact that wealthier regions experience faster-growing stocks of secondary materials than resource-producing regions, which makes downstream CE strategies much more viable and shifts their priorities away from primary resource production (Haas et al., 2023). However, the economies of many regions across the globe continue to rely on the extraction of raw materials (Bridge, 2008). Notably, less developed countries are often significantly more dependent on exploiting natural resources and thus the flow of physical materials rather than providing services (Barbier, 2019; Cantú et al., 2021).

This geographical focus is particularly problematic as territories characterised by export-oriented, specialised production of natural resources often display very different spatial configurations of economic activities than territories without natural resource extraction (Hayter et al., 2003; Lashitew et al., 2021; McElroy, 2018). Economic geographers have long emphasised the importance of spatial configurations of economic activities in shaping economic outcomes (Duranton and Kerr, 2018). In the context of CE transitions, the spatial configuration of economic activities plays a crucial role in determining a region's ability to adopt CE approaches. Research has shown that virtually all forms of transition towards more circular modes of production and consumption require increased resource sharing and interaction between economic actors (Ghisellini et al., 2016; Kirchherr et al., 2023). For example, *industrial symbiosis* and *industrial ecology* have demonstrated how local networks of businesses play a vital role in facilitating resource sharing (Chertow and Ehrenfeld, 2012; Chertow, 2009; Korhonen, 2001). Moreover, recent empirical evidence suggests that successful transitions towards more circular practices require specific spatial configurations of economic activities, not just at the local level but across broader territorial and regional scales (Bustos et al., 2021; Ghisellini and Ulgiati, 2020; Gura et al., 2023; Prendeville and Bocken, 2017; Sutcliffe and Ortega Alvarado, 2021). Specifically, the unique spatial configurations of regional and territorial economies have been shown to impact the dynamics of regional resource flows,

which are the backbone of effective application of CE approaches (Bezama et al., 2019; Bressanelli et al., 2022; Ström and Hermelin, 2023).

Consequently, we can conclude that our understanding of CE transition dynamics of critical energy transition mineral value chains is limited by two under-researched areas in the CE literature: an outsized focus on downstream value chain segments and a geographical focus on mineral-consuming regions that display specific configurations of economic activities. As a result, limited academic attention is currently given to applying CE approaches in upstream value chain segments that will play a crucial part in providing the critical minerals required for the energy transition. This has arguably constrained the development of targeted knowledge that could support upstream raw material-producing industries – often viewed as inherently dirty or polluting – and their host regions in adopting CE approaches.

2.2.3 The CE concept and mineral resource extraction activities

Despite the general tendency of the CE literature to focus more on downstream industries and regions that consume mineral resources, a small but growing body of research is examining the application of CE approaches in the mining sector. A keyword search revealed fewer than 30 papers on this topic, most of which explored specific aspects of potential CE implementation that mining companies could consider.

These papers highlight that while the mining sector predominantly operates within a *linear* economic model, CE approaches can enable mineral extraction to be conducted more sustainably. Specifically, there are numerous opportunities to establish circular flows at the mine site level, which can improve mineral extraction, minimise mineral losses to mining waste, and help mitigate some of the environmental impacts associated with mine waste disposal (Golev et al., 2020; Gorman and Dzombak, 2018). For example, several studies have demonstrated that tailings' management and reuse can be improved if mining companies adopt

CE approaches (Kinnunen et al., 2022; Kinnunen and Kaksonen, 2019; Lebre, 2018). One key area of investigation is the potential of valorising mine tailings, which represents a significant opportunity for waste reduction and resource recovery (Golev et al., 2022; Hamraoui et al., 2024; Høyli and Jakobsen, 2022; Tayebi-Khorami et al., 2019).

Furthermore, using CE strategies to reduce the consumption of inputs the industry requires, such as water, machinery, tyres, and chemicals, can significantly decrease resource use and waste in the mineral extraction process (Cisternas et al., 2022). For instance, Zhao et al. (2020, 2012) and Liu et al. (2019) explored how Chinese coal mining enterprises could adopt CE principles and strategies to reduce their environmental impact through improved resource efficiency, while Jamett et al. (2022) investigated how adopting a CE framework facilitates the transition of copper mining production processes toward more sustainable practices, emphasising its impact on managing scarce resources like water and improving cost efficiency. They all found that applying CE thinking to the sector can significantly reduce the environmental impacts of mining activities. It has also been argued that operating mines as long as minerals can be extracted at acceptable environmental costs minimises the loss of non-renewable resources, thereby aligning the mining industry with CE objectives (Lèbre et al., 2017).

It follows that there is a clear opportunity for the mining and metals industry to create value and reduce environmental liabilities from waste streams along the value chain, thereby making substantial contributions towards a CE transition (Golev et al., 2020; Tayebi-Khorami et al., 2019). However, a clear gap remains in the literature regarding the scholarly understanding of applying the CE concept to the mining sector and how extraction activities can be integrated into a more circular model.

To sum up, the CE concept has evolved significantly since its inception, expanding from a focus on waste management and industrial ecology to encompass broader economic and business model implications. This evolution has led to a more comprehensive understanding of how CE approaches can be applied across various sectors and scales. However, while the existing CE literature has significantly contributed to our knowledge of sustainable resource management, there remains a notable gap in research explicitly addressing the role of mineral extraction in a CE and the application of CE approaches to the extraction of critical energy transition minerals.

This gap is particularly significant given the projected increase in demand for these critical minerals and the potential environmental and social impacts associated with their extraction and processing. Traditional CE models and frameworks often emphasise the reduction or elimination of resource extraction. However, the reality of the energy transition necessitates continued extraction of critical energy transition minerals, at least in the short to medium term. This raises important questions about how extraction activities can be integrated into a more circular model, minimising environmental and social impacts while ensuring a stable supply of essential resources. As we transition to the next section, it becomes clear that addressing these challenges requires a more nuanced and comprehensive approach to circularity. This approach must consider all value chain segments, including extractive activities, and explore innovative CE approaches in the upstream segment of value chains.

The limitations of the existing CE literature in addressing the unique challenges of the mining sector and resource-dependent regions highlight the need for a more nuanced approach that considers the specific geographical contexts of these areas. This gap in the literature calls for an analytical framework that can capture the complex dynamics of CE application in the mining sector, particularly concerning critical energy transition minerals. Such a framework

must account for the spatial dimensions that shape economic activities and transitions in these regions.

2.3. CE implementation as a sustainability transition process situated in a spatial context

The preceding sections highlighted the limitations of applying existing insights from the CE literature to the mining sector and resource-producing regions. Building on this discussion, the following section positions the application of CE approaches in mining as a sustainability transition, while emphasising that such transitions must be understood through their spatial context.

The mining sector's application of CE approaches can be framed as a transition process. This perspective stems from the recognition that the application of CE approaches necessitates fundamental shifts in how resources are extracted, processed, utilised, and recirculated. Such shifts involve technological changes, business practices, societal norms, policies, and institutional structures (Geels, 2018; Geels et al., 2023; Köhler et al., 2019). The current mining business model is heavily dominated by a linear model of resource extraction, production, and disposal, which is deeply entrenched in economic systems and institutional frameworks (Golev et al., 2020). This means that any application of CE approaches in the sector must ultimately challenge the entrenched linear model of extraction and disposal present within the sector, and instead explore how strategies such as waste reduction, resource recovery, and more efficient use of inputs can both lessen the sector's environmental and social footprint and ensure the continued supply of critical raw materials for the energy transition.

The field of sustainability transitions research provides a valuable analytical lens for examining such transformative processes. This body of literature explores how societies can move from unsustainable socio-technical systems to more sustainable configurations,

involving profound and interdependent changes in technology, culture, policy, markets, and infrastructure (Geels, 2022, 2004; Markard et al., 2012). It provides insights into the complex dynamics of change, focusing on the interplay between established systems and emerging innovations, and offers a framework for analysing the barriers and enablers of sustainability-oriented transformations.

Sustainability transition researchers conceptualise transitions as the interplay between three analytical levels: (1) the existing landscape, (2) the existing socio-technical regime, and (3) socio-technical niches (Geels, 2018; Geels and Schot, 2007). The landscape represents broader exogenous trends and pressures, such as climate change, geopolitical dynamics, or societal expectations for sustainability (Geels, 2011). The socio-technical regime consists of dominant practices, norms, and institutions that maintain the status quo (Geels, 2004). Niches are protected spaces where radical innovations can develop and potentially challenge the existing regime (Geels, 2004; Geels and Schot, 2007).

In the case of mining, global climate goals, growing investor scrutiny, and demands for responsible sourcing and production represent strong landscape pressures, while entrenched linear production systems form the prevailing regime. Thus, CE approaches can be understood as niche practices that may gradually challenge the dominant model. However, unlike other transition contexts such as energy or mobility, the mining sector is inherently place-bound and resource-dependent. This means that the spatial characteristics of mining regions, including enclave economies, weak local linkages, and high dependence on external actors, fundamentally shape the applicability and limits of CE approaches (Bridge, 2008; Phelps et al., 2015; Lashitew et al., 2021).

These spatial realities suggest that existing CE transition models, primarily developed in industrialised contexts with different spatial circumstances, need careful adaptation before

they can be applied to extractive economies. In short, while CE in mining can be understood as a sustainability transition, it must be situated within the spatial realities of mineral-dependent regions.

2.3.1. The role of spatial configurations in shaping CE transitions in mining

The spatial dimension of sustainability transitions has gained increasing attention in recent years, with economic geographers emphasising that place-specific factors condition the pathways and outcomes of transition processes (Coenen and Morgan, 2020; Feola, 2020; Wahlund and Hansen, 2022). Like sustainability transitions research, economic geography posits that systemic changes unfold within the context of established economic activities and interactions among diverse economic actors. However, economic geography understands economic transition processes not only to be embedded in a specific socio-institutional context, but also that spatial factors strongly shape such processes (Bathelt and Glückler, 2003, 2011; Granovetter, 1992, 1985). Hence, there is a growing body of literature that recognises that the spatial context plays a crucial role in shaping the pathways and outcomes of sustainability transitions, highlighting the importance of understanding the spatial configurations of economic activities in these processes (Hansen and Coenen, 2015; Köhler et al., 2019; Truffer et al., 2015, 2015).

In particular, the spatial configuration of economic activities is critical for understanding how regional specificities and path dependencies shape economic outcomes. This includes examining the importance of regional clustering in affecting economic activities and innovation (Duranton and Kerr, 2018; Martin and Sunley, 2003). The spatial dimension is particularly relevant in the mining sector, where resource extraction is inherently tied to specific locations, creating unique regional economic landscapes (Bathelt and Glückler, 2005; Bridge, 2008, 2004). This includes the geographic distribution of mining operations, processing facilities, and the infrastructure networks that connect them.

One key perspective in this discourse is conceptualising sustainability transitions as regional diversification processes (Boschma et al., 2017). This approach emphasises the need to rearrange existing linkages within regional economies to support new types of economic activities that align with CE approaches. In this context, linkages refer to the connections and interactions between different economic actors, sectors, or activities within a particular geographic area (He and Zhu, 2016). These linkages are critical for the productive development of regions as they connect various stakeholders within and across a territory, facilitating the flow of information, resources, and technologies (Hirschman, 1977; Morris et al., 2012).

Transitioning to more circular production and consumption models necessitates increased resource sharing and interactions among economic actors within a specific territory, aiming to slow, narrow, or close material cycles (Ghisellini et al., 2016; Kirchherr et al., 2023). As a result, the spatial configurations of economic activities and linkages, such as the location and type of economic actors and the infrastructure layout, play a crucial role in CE transitions, as they influence a region's capacity to redirect resource flows (Arsova et al., 2022; Bacova et al., 2016; Bezama et al., 2019; Razminiene and Tvaronaviciene, 2018)

The importance of these interactions in fostering innovation, enhancing productivity, and driving economic growth within a region has been well-documented in the economic geography literature (e.g. Bathelt et al., 2004; Ketels and Memedovic, 2008; Krugman, 2011). Forward and backward linkages ensure companies are well-integrated into local and global value chains, providing access to markets, suppliers, and cutting-edge research and development activities. Consequently, it has been extensively argued that the *right* combination of linkages is instrumental in forming and developing so-called *industrial clusters* (Martin and Sunley, 2003; Porter, 2000). These clusters thrive on the principle of co-location, which allows businesses in a territory to benefit from shared resources such as labour, infrastructure, knowledge, and networks. In CE transitions, clusters are particularly significant as they can

serve as catalysts for developing CE practices. Linkages within these clusters are core enablers for regional resource sharing, which is an important component of promoting higher levels of circularity in a given territory (Razminiene and Tvaronaviciene, 2018).

Research on industrial symbiosis and industrial ecology has long highlighted the critical role of localised networks of economic actors in enabling resource sharing, underscoring the importance of linkages and embeddedness within industrial systems (Chertow and Ehrenfeld, 2012; Chertow, 2009; Domenech et al., 2019; Korhonen, 2001). However, there is growing empirical evidence that these insights also apply to scales beyond the hyper-local industrial setting, with regional and national sustainability transitions requiring the spatial re-configuration of territories to facilitate the successful application of CE approaches. Prendeville and Bocken (2017) argue that establishing CE practices requires developing complementary networking structures and services, such as sales platforms, product re-marketers, re-manufacturers, and reverse logistics companies. Empirical studies from different geographic contexts, such as Italy (Ghisellini and Ulgiati, 2020), Albania (Gura et al., 2023), and Norway (Sutcliffe and Ortega Alvarado, 2021), underscore the role of regional clusters and actor networks in resource circulation and sharing. Additionally, scholars have increasingly recognised the spatial dynamics of resource flows and value chains as critical to designing effective CE approaches that account for regional characteristics (Bezama et al., 2019; Bressanelli et al., 2022; Ström and Hermelin, 2023).

However, as already discussed in Section 2.1.3., in many mining territories these regional clusters are often absent. Instead, mining territories are often characterised by economic enclavism, weak horizontal linkages, and outward-oriented export structures. As a result, the kinds of circular practices that rely on clustering, such as local reuse of by-products or regional sharing of waste streams, are arguably more challenging to establish in mining economies than in industrial districts or metropolitan regions. This absence of clustering does

not mean, however, that CE approaches are irrelevant to mining. Instead, it suggests that their relevance must be framed differently. At the mine-site level, CE principles can guide practices such as waste valorisation, water reuse, and improved resource efficiency (Golev et al., 2020; Kinnunen and Kaksonen, 2019; Lebre, 2018). At the regional level, CE thinking provides a framework for diversification with the aim of improving the regional capacity of resource circulation (Cisternas et al., 2022; Kinnunen et al., 2022; Ström and Hermelin, 2023).

Another crucial aspect shaping the spatial configuration of economic activities is institutional dynamics. Encompassing formal and informal rules, norms, and practices, they are crucial in shaping regional trajectories of social and economic development (Gertler, 2018). They influence the application and implementation of changes to economic activities within specific regional contexts. As a result, the CE is increasingly conceptualised not as an array of dispersed business practices or strategies but as a field of institutional experimentation shaped by distinct institutional conditions (Fischer et al., 2021; Schulz et al., 2019). Institutions, broadly defined as economic and industrial systems that entail multidimensional configurations of economic and political agencies (Henrysson and Nuur, 2021), play a pivotal role in delineating the spectrum of possible economic activities. They influence who bears the costs of externalities, encompassing both social (e.g., inequalities) and environmental (e.g., air and water pollution) impacts (Bromley, 1989).

These institutional dynamics shaping CE implementation are deeply rooted in regional contexts. Ghisellini et al. (2016) emphasise that the transition towards a circular economy requires not only technological innovations but also significant institutional and social changes in a regional context. In the case of mining, these institutional factors are often closely tied to local and regional governance structures, cultural norms, and historical patterns of resource exploitation. Understanding these spatially-specific institutional arrangements is therefore crucial for developing effective CE approaches for the mining sector, as they can either

facilitate or hinder the implementation of circular practices (Abreu and Ceglia, 2018; Bauwens et al., 2020).

Taken together, these insights suggest that spatial configurations, encompassing linkages, clustering, and institutions, are central to understanding how CE transitions might unfold in mining. They highlight why simply transferring CE models from manufacturing or urban contexts is insufficient, and why a more context-sensitive approach is required. Therefore, it can be argued that mining's spatial realities may constrain specific CE approaches, but they also create niches where others, particularly those focused on resource efficiency, waste reduction, and regional diversification, can be meaningfully applied.

2.4. Chapter conclusion

The CE concept provides a valuable framework and systems thinking approach for navigating the transition towards more sustainable extraction practices. In particular, the concept offers potential solutions to the pressing issues of material management, waste disposal, and the outsized sustainability impacts associated with extractive industries. Furthermore, it presents opportunities to address the challenges of enclave economies by promoting more regional circulation of materials and fostering localisation economies.

It is crucial to recognise that the application of CE approaches represents a transition process. This transition involves the gradual transformation of existing socio-technical regimes towards new systems that support more circular modes of production. The spatial dynamics that underpin this transition process are complex and multifaceted. They involve reconfiguring material flows, developing new industrial networks, and reshaping regional economic structures, highlighting the importance of place-specific factors in shaping these transitions, including local institutional arrangements, regional innovation systems, and path dependencies. The remainder of this thesis will explore these spatial dimensions of CE transitions in the

context of critical energy transition minerals. It will examine how the specificities of the mining sector and its host regions influence the potential for circularity, and how CE approaches can be leveraged to address the environmental, social, and economic challenges associated with increased mineral extraction.

The meta-thinking presented in this chapter will guide this project, serve as a lens to understand the barriers and drivers of CE approaches in the mining sector and investigate the existing state of CE implementation in Chile's mining sector. Finally, it enables exploring ways to transition the industry towards a system that enables the development and application of more circular modes of production rather than inhibiting them. The following section will discuss the research design and methods used in this research project.

3. Research design and methods

In line with the problem-oriented approach of this thesis, the three empirical chapters (Chapters 4-6) of this thesis utilise a wide range of social science techniques to analyse the implementation of CE approaches in the mining industry. Each of these chapters includes its own methods section in line with journal requirements. Hence, this chapter aims not to duplicate this effort but to tell the story of the iterative journey that led to this project's final research design, the choice of fieldwork locations, and the rich insights from the fieldwork that did not make it into three empirical articles. Additionally, it will discuss the ontological and epistemological foundations of the chosen research methods and critically examine my positionality.

This thesis employs a mixed-methods approach. I conducted two separate studies, one quantitative and one qualitative, which combined quantitative material flow modelling and

qualitative interview-based analysis to comprehensively examine the implementation of CE approaches in the mining sector and resource-dependent regions. The quantitative study assesses the limitations of end-of-life recycling strategies for meeting future metal demand to establish the need to consider circular practices in primary production. Building on this foundation, the qualitative study utilises semi-structured interviews and focus groups to explore the conceptual and practical challenges of implementing CE approaches in mining operations and resource-rich regions. By integrating macro-level material flow insights with micro-level perspectives from industry stakeholders, this methodology allows for a multi-faceted investigation of both the theoretical and applied aspects of circular transitions in the mining industry. This research design enables a comprehensive examination of the research questions, providing insights into the limitations of current circular economy approaches, the potential for circular practices in primary mineral production, and the spatial dynamics influencing circular transitions in mining territories.

The remainder of this chapter will first describe this project's methodological framing. This will be followed by a description of the research design and a discussion of the methodological approaches and case studies chosen to answer the research questions before concluding with a critical examination of the chosen research method's limitations.

3.1. Research framing

This research project is grounded in the paradigm of critical realism (CR) (Bhaskar, 1978). CR provides a robust theoretical foundation for studying complex social phenomena and offers a nuanced ontological framework that allows researchers to explore observable events and the underlying causal mechanisms driving change. As explored in the previous chapter, the CE paradigm can be understood as a conceptual framework to guide the transition to restructure

economic activities and industrial production and consumption to be more compatible with a healthy natural environment.

The research approach also recognises the CE paradigm as a conceptual framework guiding the transition towards restructuring economic activities and industrial production and consumption to be more compatible with a healthy natural environment. This understanding situates the implementation of CE approaches within the broader context of *sustainability transitions*. By framing CE adoption in the mining industry as a sustainability transition, the research can draw on the relevant transition theories and concepts discussed in the literature review. This allows for a more comprehensive understanding of the challenges and opportunities in transitioning a traditionally linear industry towards more circular practices.

3.1.1. Unpacking Sustainability Transitions through Critical Realism

CR offers a nuanced ontological foundation for examining complex social phenomena, such as sustainability transitions. In contrast to other philosophies of science, such as positivism and pragmatism, in CR, outcomes are generated by (inter)actions of agents with causal powers, mediated by structures and causal mechanisms (Geels, 2022). Developed by the British philosopher Roy Bhasker in the 1970s, CR posits a layered ontology comprising the *real, actual, and empirical domains* (Bhaskar, 1978). It emphasises generative causality, where observable events are shaped and actively produced by the underlying structures of reality (Saunders et al., 2009). As shown in Figure 3.1, this layered ontology allows for an analysis that moves beyond the observable to understand the deeper, generative mechanisms driving sustainability transitions.

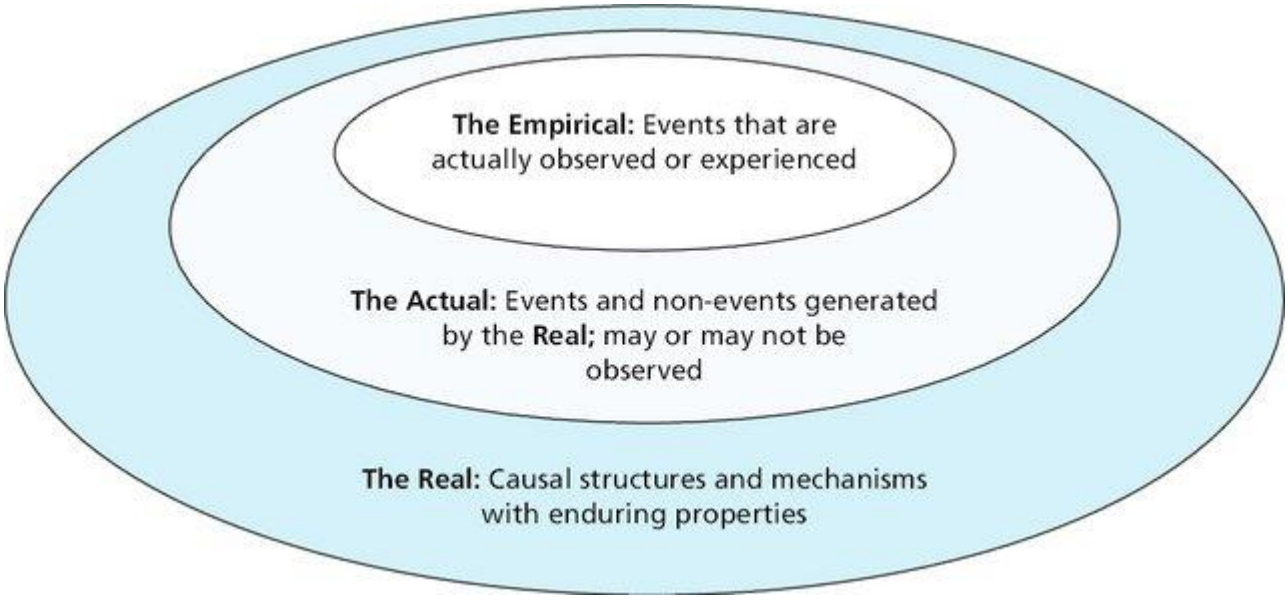


Figure 3.1: Critical realism's layered ontology developed by Bhaskar (1978)

The *real domain* is the deepest layer of social reality. It comprises the complex web of underlying structures, generative mechanisms, and causal powers crucial in distributing resources and authority to different actors within a social setting, enabling or constraining the actions they can take (Danermark et al., 2001). In the context of this research project, this might involve market forces driving demand for more sustainable mining practices, policy frameworks that incentivise or mandate circular approaches, technological innovations enabling new forms of resource recovery, the organisational culture in the mining industry, cultural shifts in societal expectations regarding resource use and environmental stewardship, and power dynamics within the mining industry and mining regions that influence decision-making around sustainability. The real domain is crucial for understanding phenomena's deeper drivers, allowing researchers to move beyond surface-level observations to explore the fundamental mechanisms of change (Bygstad et al., 2016; Danermark et al., 2019).

The *actual domain*, in contrast, encompasses all events that occur, whether observed or not. Within this domain, individuals perform actions or refrain from performing actions, leading to events or the lack thereof. The complex web of structures of the *real domain* governs

these actions. However, although structures enable and constrain action, actors' actions also create, maintain, and change these structures (Sayer, 2010). Hence, while the structures of a social system govern the actions available to actors within a social system, they have agency and can choose to perform actions that either reproduce the system's structures or change them (Reed, 2000). In the context of this research project, this could include actors' actions to shift organisational practices or supply chain dynamics to promote CE practices, alterations in local economic structures due to new circular business models, and improved resource efficiency and environmental performance. Understanding the *actual domain* requires looking beyond immediate observations to capture the full scope of how sustainability transitions unfold (Sayer, 2000).

Finally, the *empirical domain* is the surface level of social reality and encompasses observable events and experiences. These observations and experiences result from actions and events in the *actual domain*. In this context, it might include visible changes in waste management practices at mine sites, the implementation of new technologies for resource recovery, the establishment of partnerships for material reuse or recycling, and changes in corporate reporting on sustainability metrics. While these observable phenomena represent only the 'tip of the iceberg', they are crucial for empirical research as they provide tangible evidence of change (Easton, 2010; Fletcher, 2017).

In CR, theories act as *lenses*, *tools* or *heuristics* for explaining concrete instances of social phenomena (Danermark et al., 2019; Maxwell, 2012). They offer conceptual tools for understanding the interactions between actors, activities, structures, and causal mechanisms. However, there are two primary understandings of how theories explain change within CR (Geels, 2022). The first, primarily associated with the works of Bhaskar (1978) and Sorrell (2018), is more objectivist, formal, and structural. It posits that the causal powers of entities are inherently derived from the internal structure of their components. In contrast, the second

understanding of CR, primarily attributed to Harré (2009, 1986) and Archer (1995), adopts a more agentic and processual perspective. This interpretation of CR argues that causal powers are actualised through social action and interaction, which are invariably situated and shaped by their context.

Given the complex nature of CE transitions, which involve intricate interactions between technological innovation, policy frameworks, market dynamics, and societal expectations, CR's agentic, processual understanding offers several advantages for this research. First, it acknowledges the role of context, which is crucial in understanding the mining industry's unique challenges and opportunities in adopting CE principles. Second, it conceptualises transition processes as interactions between multiple actors, events, corporate and policy actions, and choices. This aligns well with the reality of CE transition, which requires involvement from various stakeholders across different industries and policy domains. Third, it offers a more nuanced and flexible framework for examining the non-linear, multi-level, and context-dependent nature of sustainability transitions (Geels, 2011; Geels and Schot, 2007). These characteristics pose significant challenges for more structural cause-and-effect approaches, which often struggle to accommodate the complexity and dynamism of transition processes (Geels, 2022, 2020).

As a result, the agentic, processual understanding allows for a more comprehensive examination of the various actors, processes, and contextual factors that influence the implementation of CE approaches in the mining sector while also acknowledging the dynamic interplay between structure and agency that makes the nature of sustainability transitions non-linear and often unpredictable (Köhler et al., 2019). As such, it facilitates a more nuanced understanding of how various stakeholders navigate and negotiate the transition process and how their actions are both constrained and enabled by existing structures and contextual factors. This interpretation of CR thus provides a robust theoretical foundation for exploring

the complex processes of CE implementation in the mining industry, offering insights that can inform both theory and practice.

3.1.2. A Critical Realist Understanding of CE Implementation in the Mining Sector

Employing this layered ontology allows researchers to integrate observable practices (empirical), their broader impacts (actual), and the underlying drivers of change (real). For instance, it facilitates examining how underlying economic structures in the real domain manifest in specific CE practices in the actual domain or how observed changes in waste management in the empirical domain relate to broader shifts in industry dynamics in the actual domain. However, given the complexities inherent in sustainability transitions, it is impossible to comprehensively explore all aspects of CE implementation within a specific sector, such as mining. Therefore, based on the gaps identified in the existing literature outlined in Chapter 2, I chose to focus on areas where our understanding of the applicability of the CE concept and its associated practices in the mining sector remains limited. CR provides a flexible framework for investigating these selected aspects while acknowledging the broader context and interconnections within the system.

The use of CR in this research problem involves several key elements. Firstly, it recognises the mining industry's specific context, acknowledging that mining is situated in a particular industrial and spatial context, impacted by policy choices and external events. This contextual understanding is crucial for interpreting the challenges and opportunities for CE adoption in the sector, as extractive industries and resource-dependent regions display significantly different dynamics from many of the more commonly studied cases in the CE literature.

Secondly, the research explores interactions between multiple actors, examining how various stakeholders, including mining companies, policymakers, local communities, and other

industries, interact in the process of implementing CE approaches. This multi-actor perspective aligns with CR's understanding of change processes as complex interactions. Furthermore, the research investigates causal mechanisms to uncover the underlying factors that drive or hinder CE implementation in the mining industry. This involves looking beyond surface-level events to understand the deeper structures and processes.

Lastly, the research acknowledges the role of agency, recognising that individual and collective actions play a significant role in shaping the transition towards CE in the mining industry. This aligns with the agentic understanding of CR, emphasising the importance of human action and decision-making in driving systemic change. By incorporating these elements, CR enables a comprehensive yet focused examination of CE implementation in the mining industry, allowing for a nuanced understanding of the complex interplay between context, actors, mechanisms, and agency in this transition process. The next sub-section will delve into the research design employed in this project, exploring aspects of the reflexive journey that led to the chosen study design, before outlining the methods and approaches used to investigate these specific aspects of implementing CE approaches in the mining sector and resource-dependent regions.

3.2. Research design

3.2.1. Positionality and reflexive journey

The research design for this thesis evolved significantly throughout the course of the project. In particular, my professional background and positionality deeply influenced this project's research design. It shaped not only the project's direction but also how I engaged with the concept of the circular economy. Prior to embarking on this research project, I worked in sustainability-related roles within the mining sector for several years. This experience gave me unique insights into the operational challenges that mining companies face when striving to

become more sustainable. In particular, I saw first-hand the vast potential for embedding CE thinking into mining operations to address some of the sector's most pressing issues, such as the large amounts of structural waste produced in the extraction of minerals in the form of tailings, rock waste and slags.

In addition, my professional background facilitated an atypical insider-outsider positionality during the data collection process, particularly when conducting interviews. My industry experience enabled me to position myself as both an insider, familiar with the sector's intricacies, and an outsider, now approaching the field as a researcher. This dual status significantly influenced how interviewees perceived and interacted with me. During interviews with mining sector stakeholders, I deliberately presented myself as a peer, leveraging my industry knowledge to establish rapport and credibility. This approach proved highly effective, as interviewees often opened up, viewing me as 'one of them'. They frequently used industry-specific jargon and referenced shared experiences, assuming a level of understanding that might not have been present with a researcher lacking an industry background. This insider status granted me access to individuals, insights and candid opinions that might have been inaccessible to an outsider. For instance, interviewees were forthcoming about the significant industry-wide cultural barriers to implementing CE practices and challenges of mistrust from host communities and government entities towards the sector, often sharing anecdotes that provided valuable context. However, I tried my best to remain cognisant of the potential drawbacks of this insider position and attempted to maintain the critical distance necessary for rigorous academic research.

This positionality also shaped my initial framing of the research problem. Due to my technical expertise and constant conversations with experts with deep knowledge of sustainability-related concepts, I approached the research with the assumption that the CE concept and its associated principles were widely understood and seen as part of the solution

to the mining sector's sustainability challenges by stakeholders in the mining industry and its surrounding academic and policy circles. As a result, I initially approached the research with a focus on how CE approaches could be *operationalised* within the mining sector, as I had assumed the primary knowledge gap to be one of implementation rather than conceptualisation.

However, this assumption was challenged early on in the project. As I delved deeper into the research process, I realised that my positionality had led me to make certain assumptions that were not universally shared. During the initial phase of research, which included a preliminary literature review and informal discussions with a broader range of stakeholders in the mining sector and academia beyond the sustainability professionals in the industry I mostly interacted with, I discovered that the concept of the CE was far more contested and less familiar to many than I had anticipated. On the one hand, I discovered that the dominant CE literature implicitly assumed that the primary production of raw materials lay outside the CE paradigm. This assumption conflicted with my practical understanding of the mining industry's role in material production and with real-world metal cycles. In particular, based on my first-hand professional experience, I recognised that the view of a *full* or *true* circular economy without any primary metals extraction is incompatible with the reality of how metals are produced, consumed, collected, recycled, and reused. On the other hand, contrary to my initial belief, while sustainability professionals in the sector often recognised CE as a valuable framework, I found that many decision-makers without sustainability expertise in industry and policy had limited understanding of the CE concept. Many viewed it as applicable only to downstream segments of metals value chains, such as recycling and EoL product waste management - business areas that most mining companies are generally not engaged in anymore due to an unwinding of the formerly common vertical integration in metals value chains over the past decades (Pietrobelli et al., 2024).

This realisation led me to adopt a more reflexive stance, critically examining my preconceptions and how they had influenced my research design. This process prompted a fundamental shift in my research practice and led me to alter my research design and methodology. Instead of focusing solely on *operationalising* CE approaches in the mining industry, I decided to take a step back and address more fundamental questions about the role of primary production in the transition towards a circular economy. Realising the gaps in the CE literature's applicability to the upstream segments of the mining value chain led to a two-fold aim for the research: (1) to make a case for why making raw material extraction processes more circular is essential to the transition to a CE, and (2) to generate additional evidence that can guide the application of CE approaches in the mining sector.

This shift in my understanding of the research problem necessitated fundamental alterations to the originally envisioned research design. Firstly, rather than relying solely on quantitative methods as initially planned, I decided to split the project into two separate but interconnected studies: one quantitative and one qualitative. The quantitative study focused on material flows of the global copper cycle. By exploring the limitations of recycling, the most widely studied and promoted downstream CE strategy that is often positioned as an alternative to primary production, I aimed to demonstrate the insufficiency of relying only on downstream CE strategies and make a case for the importance of not overlooking opportunities presented by implementing CE approaches in upstream value chain segments. Secondly, prompted by the realisation that there was a lack of conceptual tools for CE implementation in upstream value chain segments, the second fundamental change to the research design was a shift away from focusing on the techno-economics of *operationalising* CE practices towards developing a conceptual foundation for the implementation of CE approaches in the mining industry.

Even after establishing this revised research design, I continuously reassessed and reiterated aspects of the study (see Figure 3.2). In particular, the two studies informed each

other in an iterative process. For instance, insights from the quantitative study's literature review helped inform the conceptual gaps that the qualitative study subsequently investigated. This iterative approach aligns with the principles of *adaptive theory* (Layder, 1998), emphasising the interplay between existing theory and emerging data in shaping research design. Furthermore, I employed a staggered interview approach to help identify the most suitable case study location for the qualitative study. The first round of interviews with global experts informed the decision to conduct intensive fieldwork in Chile. This approach to case selection is consistent with the purposive sampling strategy often used in qualitative research, where cases are selected based on their potential to provide rich, relevant data (Patton, 2014)

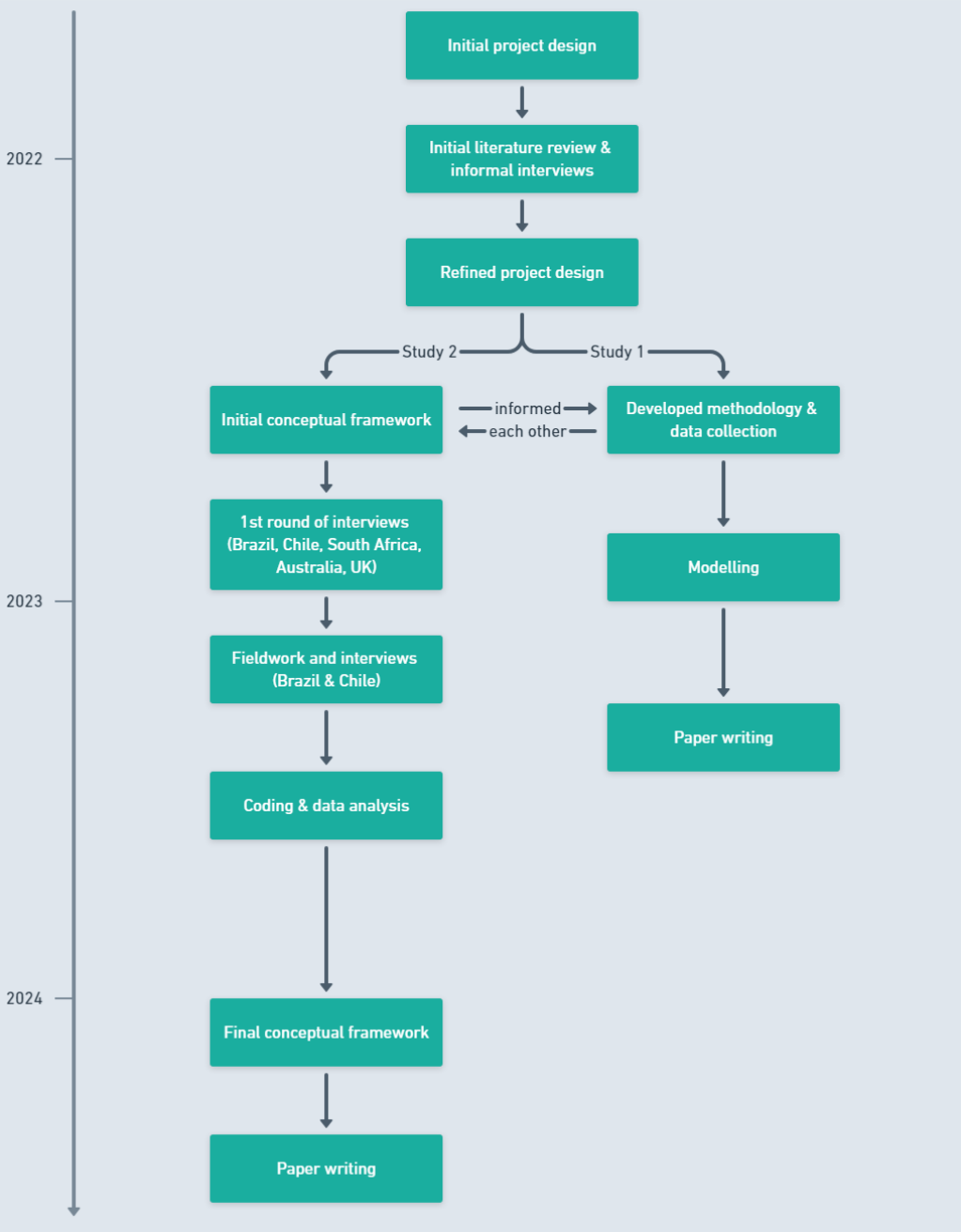


Figure 3.2: Reflexive research design journey

The research process also encountered several unexpected challenges that necessitated further adjustments to the study design. Despite my personal connections within the mining industry, securing access to mine sites and obtaining data from mining firms proved more difficult than initially anticipated. This limitation constrained the planned comparison between firm and/or site-level and industry-wide strategic perspectives on CE implementation. For

instance, a fieldwork trip to a large-scale iron ore mine in Brazil, which I had hoped would allow me to gather empirical data for a case study on the micro, firm-level dynamics of CE adoption, did not yield the desired results. Despite building a good rapport with the local team in Brazil, spending a week on-site and carrying out numerous interviews, the company's global management imposed restrictions on data access and publication, which ultimately forced me to abandon both the Brazilian case study and the firm-level analysis component of the research.

Similarly, my original plans to conduct a mixed-method case study in Chile had to be modified. While I successfully conducted semi-structured interviews and focus groups, a planned structured survey of CE adoption among mining firms active in Chile, to be carried out in collaboration with a local Chilean organisation, was indefinitely postponed due to funding issues encountered by the partner organisation. This delay made it unfeasible to wait for the survey's completion within the timeframe of my doctoral studies. Consequently, the Chilean case study now relies solely on qualitative data from semi-structured interviews and focus groups.

This reflexive journey and the resulting changes in research design highlight the importance of researcher positionality and reflexivity in research (Berger, 2015). My initial assumptions, shaped by my professional background, were challenged and revised through the research process, leading to a more nuanced and comprehensive study design. This experience aligns with Finlay's (2002) assertion that reflexivity in research can lead to unexpected insights and directions, enriching the research process and its outcomes. In addition, the changes to the research design I had to make taught me first-hand the importance of flexibility and adaptability in research design, particularly when studying complex industrial sectors. In particular, they highlighted the potential barriers researchers may face when attempting to access sensitive corporate data, even with pre-existing industry connections (Welch et al., 2002). Despite these setbacks, the adapted research design still allowed for a comprehensive exploration of CE

adoption in the mining sector, albeit with a greater emphasis on qualitative methods and broader industry perspectives rather than firm-specific case studies.

3.2.2. Research methods

The reflexive process resulted in choosing an integrated thesis approach for this project that employed both quantitative and qualitative research methods to answer the research questions posed. However, rather than 'mixing' the two approaches as usually done in 'mixed methods' research approaches (Halcomb and Hickman, 2015), I conducted two separate studies, one quantitative and one qualitative. The two studies investigate different elements of the same research problem and, therefore, do not use overlapping data.

While the quantitative study provides a macro-level assessment of material flows and recycling potentials and highlights the limited scholarly and policy focus on the implementation of CE approaches in the upstream segments of global value chains, the qualitative analysis offers micro-level insights into the operational, regional, and institutional dynamics of transitioning these upstream activities towards more circular practices. The distinct yet complementary nature of the methods allows for the exploration of the theoretical and practical dimensions of CE transitions in the mining industry and the unique geographic context of resource-dependent regions while also facilitating a discussion of the broader question of how the materials necessary for a global energy transition can be secured without large negative externalities. While the first study produced one paper primarily focused on establishing the significance of the broader research problem and answering RQ 1 and RQ2, the second study produced two papers aimed at answering RQs 3-7. An overview of each paper, including their aim and the methods and the data used, can be found in Figure 3.3.

	DESCRIPTION	RESEARCH QUESTIONS	METHODS	DATA / INPUTS	STATUS	JOURNAL
Paper 1: The limitations of end - of-life copper recycling and its implications for the circular economy of metals	This paper evaluates the potential of EoL recycling strategies to meet future metal demand and replace primary production	**RQ 1:** How does the forecasted demand for critical energy transition minerals impact the ambition of transitioning to a circular economy? **RQ 2:** What are the limitations of downstream CE strategies (e.g. recycling) for critical energy transition minerals sourcing?	**Quantitative** Dynamic Probabilistic Material Flow Analysis	Secondary data from previously published studies	**Published** on 4th November 2023.	Resources, Conservation and Recycling
Paper 2: Application of Circular Economy Approaches in the mining sector: evidence from Chile	This paper investigates the current state of the application of CE approaches in the mining sector and identifies potential CE approaches to address sectoral sustainability challenges	**RQ 3:** What is the existing understanding of the role of critical energy transition minerals' extraction in a circular economy? **RQ 4:** What role can CE strategies and practices play in making primary mineral extraction processes more responsible? **RQ 5:** How can CE principles, strategies and practices be integrated into primary mineral extraction processes?	**Qualitative** Semi-structured interviews & thematic content analysis with a focus on Chile	31 individual semi - structured interviews and 11 focus group interviews with 53 participants from over 7 countries & a review of company reports and documents	**Published** on 21st February 2025	Resources Policy
Paper 3: Exploring the Spatial Dynamics of Circular Economy Transitions: Insights and Lessons from Chile's Mining Territories	This paper examines the role of space and spatial configuration of economic activity in enabling CE adoption in resource - dependent regions	**RQ 6:** What are the barriers and enablers for CE transitions in mineral resource -dependent regions? **RQ 7:** How does the spatial configuration of economic activity in mineral resource -dependent regions affect their ability to transition towards a more circular regional industrial ecosystem?	**Qualitative** Single case study of Chile based on semi -structured interviews & thematic content analysis	20 individual semi - structured interviews and 7 focus group interviews with 38 participants in Chile & a review of company reports and documents	**Published** on 20th April 2025	Progress in Economic Geography

Figure 3.3: Overview of Papers

Despite the two studies' different approaches, they are held together by various themes. Firstly, each paper tells a crucial part of the story of why the material intensity of the energy transition demands a fundamental re-think of how our society obtains materials for its technological advancement. Secondly, all of the papers are related to copper. Due to its high levels of existing anthropogenic stocks and the fact that it is the principal material that enables electrification, copper is a bellwether for the impacts of the energy transition on the future of mineral extraction. Next, I will briefly discuss the methods used in the two studies.

3.2.2.1. Study 1: Material flow modelling

The initial study focuses on developing a new method to quantify how much future demand for a particular metal can be supplied by the recycling of an already existing anthropogenic stock of this metal to uncover the importance of increasing research and policy efforts to promote CE practices in the upstream segments of metal value chains. In particular, it explores the limitations of the current focus of the CE literature and policy efforts on end-of-life

recycling strategies by quantitatively assessing recycling strategies' potential to fulfil future copper demand.

One of the well-known methodologies to quantify resource flows and understand the availability of anthropogenic stock of metalliferous materials is Material Flow Analysis (MFA) (Brunner and Rechberger, 2016). To assess the potential of recycling strategies in fulfilling future metal demand and replacing primary production, the study developed a novel type of material flow analysis (MFA) model. Unlike previous MFA studies, the model uses dynamic probabilistic elements to explicitly explore the potential of recycling to reduce metal mining activities while considering uncertainties in future end-of-life product collection and recycling rates.

The general principles underpinning this model are based on the dynamic probabilistic material flow analysis (DP-MFA) modelling approach (Bornhöft et al., 2016). The study used the case of copper, arguably one of the most critical minerals for the energy transition, to test and validate the modelling methodology and draw conclusions for future research on CE strategies. The foundation of the analysis in the study is a top-down global open-cycle dynamic stocks-and-flow model (Müller et al., 2014) that estimates historic copper flows and stock levels from 1910 until 2050. The global scope of this study and the informal nature of the secondary copper market made collecting primary data for model inputs challenging. As a result, all model inputs are based on secondary data from previously published studies.

3.2.2.2. Study 2: Interviews and thematic content analysis

The second study explores the conceptual limitations of CE approaches in the context of mineral resource extraction and the role of space and spatial configurations of economic activity in the transition towards more circular regional industrial ecosystems. It leverages the unique economic and geographic context of Chile, a country characterised by its heavy reliance

on copper and lithium mining, to examine how different spatial configurations impact the ability of regions to transition towards a more circular regional industrial ecosystem, as well as the role that CE practices currently play in promoting more sustainable production practices in the mining industry.

The primary data were collected through 31 individual semi-structured interviews and 11 focus group interviews with experts and decision-makers, including business leaders, government officials, and academics. Additionally, I visited four mine sites in Chile and one in Brazil, where I received tours of the operations and spoke with operational staff at the sites. I also took over 100 pages of field notes, which included insights from the interviews and site visits. This primary data was supplemented by secondary data, including company reports, production statistics, and news reports, to enhance the qualitative findings.

In economic geography, interviews with business executives and government officials are recognised as an effective means to gather insights into the spatial dynamics of firms and their strategic motivations (Breul and Revilla Diez, 2021; Schoenberger, 1991). Despite its effectiveness, this approach is not without its challenges, including the difficulty of securing time with busy business figures and government officials, and the dependency on the candidness and transparency of the respondents (Clark, 1998; Welch et al., 2002). Nevertheless, interviews with elites and technical experts are considered a direct window into the operational realities of businesses and public sector decision-making, offering valuable perspectives to researchers (Hughes, 1999).

The interviews were conducted during fieldwork in Brazil, Chile, and South Africa and through online videoconferencing platforms between January 2022 and February 2024. I initially conducted 14 semi-structured interviews with global experts from the United Kingdom, Australia, Canada, Brazil, Chile, and South Africa. The results of these initial

interviews led me to focus on the case of Chile, where I conducted semi-structured interviews with 21 participants and five focus group interviews with 19 participants. I had initially intended to conduct only semi-structured interviews, but during the fieldwork, I was sometimes only able to secure time with groups of experts, which led me to run these interviews as focus groups instead.

These interviews sought to capture a comprehensive view of the Chilean mining sector ecosystem, encompassing national and international lead mining firms, public authorities, and international and Chilean mining service providers and suppliers. While paper 2 incorporated insights from all interviews (Phase 1 and 2), paper 3 only used insights gained from Phase 2 interviews conducted in Chile (see Table 3.1).

#	Position	Location	Organisation	Type	Interview type	Paper 2	Paper 3
Phase 1 - Global							
1	Manager (Sustainability)	United Kingdom	Mining firm	Business	Semi-structured interview	✓	
2	CEO	Canada	Consultancy	Business	Semi-structured interview	✓	
3	Director (Innovation & Circular Economy)	United Kingdom	Industry association	Business	Semi-structured interview	✓	
4	Manager (Circular Economy)	United Kingdom	Mining firm	Business	Semi-structured interview	✓	
5	CEO	Australia	Consultancy	Business	Semi-structured interview	✓	
6	Director (Circular Economy)	Canada	Mining firm	Business	Semi-structured interview	✓	
7	Professor	South Africa	University	Academia	Semi-structured interview	✓	
8	Professor	South Africa	University	Academia	Semi-structured interview	✓	
9	Environmental Engineer	Brazil	Mining firm	Business	Semi-structured interview	✓	
10	Manager (Mining)	Brazil	Mining firm	Business	Semi-structured interview	✓	
11	Manager (Social)	Brazil	Mining firm	Business	Semi-structured interview	✓	
12	Manager (Sustainability)	Brazil	Mining firm	Business	Semi-structured interview	✓	
13	Manager (Environmental)	Brazil	Mining firm	Business	Semi-structured interview	✓	

#	Position	Location	Organisation	Type	Interview type	Paper 2	Paper 3
14	Manager (Innovation)	Brazil	Mining firm	Business	Semi-structured interview	✓	
Phase 2 – Chile case study							
15	Executive Director	Chile	Supplier	Business	Semi-structured interview	✓	✓
16	Policy-maker	Chile	National government	Government	Focus group interview	✓	✓
17	Policy-maker	Chile	National government	Government	Focus group interview	✓	✓
18	Policy-maker	Chile	National government	Government	Focus group interview	✓	✓
19	Policy-maker	Chile	National government	Government	Focus group interview	✓	✓
20	Policy-maker	Chile	National government	Government	Focus group interview	✓	✓
21	CEO	Chile	Supplier	Business	Semi-structured interview	✓	✓
22	Programme Manager	Chile	Development agency	Government	Focus group interview	✓	✓
23	Programme Officer	Chile	Development agency	Government	Focus group interview	✓	✓
24	Programme Officer	Chile	Development agency	Government	Focus group interview	✓	✓
25	Board member	Chile	Mining firm	Business	Semi-structured interview	✓	✓
26	Director	Chile	Industry association	Business	Semi-structured interview	✓	✓
27	CEO	Chile	Industry association	Business	Semi-structured interview	✓	✓
28	Director	Chile	Consultancy	Business	Semi-structured interview	✓	✓
29	Professor	Chile	University	Academia	Semi-structured interview	✓	✓
30	Advisor (Technology and Market)	Chile	Mining firm	Business	Semi-structured interview	✓	✓
31	CEO	Chile	Public-private partnership	Business/ Government	Semi-structured interview	✓	✓
32	Project Leader (Mining)	Chile	National government	Government	Semi-structured interview	✓	✓
33	CEO	Chile	Supplier	Business	Semi-structured interview	✓	✓
34	Assistant Professor	Chile	University	Academia	Semi-structured interview	✓	✓
35	CEO	Chile	Public-private partnership	Business/ Government	Focus group interview	✓	✓
36	Director	Chile	Public-private partnership	Business/ Government	Focus group interview	✓	✓
37	Manager	Chile	Public-private partnership	Business/ Government	Focus group interview	✓	✓

#	Position	Location	Organisation	Type	Interview type	Paper 2	Paper 3
38	Manager	Chile	Public-private partnership	Business/ Government	Focus group interview	✓	✓
39	Programme Manager	Chile	Development agency	Government	Semi-structured interview	✓	✓
40	Executive Director	Chile	Public-private partnership	Business/ Government	Semi-structured interview	✓	✓
41	Head of Sustainability	Chile	Mining firm	Business	Semi-structured interview	✓	✓
42	Programme Manager	Chile	Consultancy	Business	Semi-structured interview	✓	✓
43	President	Chile	Industry association	Business	Semi-structured interview	✓	✓
44	Executive Director	Chile	Research institute	Academia	Semi-structured interview	✓	✓
45	Country Director	Chile	Lead firm	Business	Semi-structured interview	✓	✓
46	Professor	Chile	University	Academia	Semi-structured interview	✓	✓
47	Manager (Sustainability)	Chile	Mining firm	Business	Focus group interview	✓	✓
48	Environmental Engineer	Chile	Mining firm	Business	Focus group interview	✓	✓
49	Environmental Engineer	Chile	Mining firm	Business	Focus group interview	✓	✓
50	Programme Manager	Chile	National government	Government	Semi-structured interview	✓	✓
51	Director	Chile	National government	Government	Focus group interview	✓	✓
52	Programme Manager	Chile	National government	Government	Focus group interview	✓	✓
53	Senior Consultant (Sustainability & Circular Economy)	Chile	Consultancy	Business	Focus group interview	✓	✓
54	Consultant (Sustainability & Circular Economy)	Chile	Consultancy	Business	Focus group interview	✓	✓

Table 3.1 Overview of interviews conducted during the research project

In both phases, interviewees were selected based on a judgement sampling approach. I created a non-random sample of interviewees based on their knowledge of the topic under investigation and their position within decision-making structures. The author's personal connections, industry events, and professional networking sites such as LinkedIn facilitated the

selection. I also used snowball sampling methods, where previous interviewees connected me with other interviewees.

The study utilised an *exploratory design* approach (Brink and Wood, 1997) anchored in critical realism (CR). As discussed earlier in this chapter, CR philosophy argues that merely describing data is insufficient to move beyond surface-level descriptions to uncover deeper insights. As a result, CR approaches require one to engage in an abductive process to infer underlying reasons and uncover causal mechanisms from the available data (Fletcher, 2020). Central to this approach is abductive theory generation, a sensemaking process involving the critical and creative step of discovering generative ideas or conjectures (Weick, 1995) (Danermark et al., 2001). These initial insights serve as the foundation for further theoretical development, which can be refined through logical deduction and tested via empirical induction (Sætre and Van De Ven, 2021).

Influenced by Fletcher (2017), I implemented a multi-stage methodological approach. The process began with data collection through semi-structured and focus group interviews, which were audio-recorded, transcribed, and supplemented with field notes. This was followed by an initial coding phase, systematically analysing the transcripts and notes to identify key empirical categories. The next stage involved abductive analysis, where the previously identified codes were reinterpreted through the lens of existing theoretical concepts. Through this process, I identified relevant emerging themes. In the final stages of coding and analysis, I integrated the identified themes with existing theories, seeking to develop a more comprehensive understanding of the research subject. This integration process involved critically examining how the emergent themes aligned with, challenged, or extended existing theoretical frameworks.

This methodological approach enabled a nuanced and multi-layered analysis of the empirical data. It was chosen ahead of alternatives like corporate document analysis or quantitative methods like input-output analysis, which offer less qualitative depth and flexibility in adapting to new insights. Given the exploratory nature of this project's research questions regarding the role of the mining sector in CE transitions and the mechanisms enabling or inhibiting these transitions, a research approach allowing for an in-depth investigation of the complex contextual factors and underlying causal mechanisms shaping CE implementation was deemed to be particularly valuable. In particular, the semi-structured interview format, combined with the abductive coding and analysis approach, gave me the necessary flexibility to provide insights into the institutional dynamics and spatial configurations that influence transition processes.

3.2.3. Limitations of the research design

While this thesis' research design and methodology yield valuable insights, they are not without limitations. This section aims to critically self-evaluate these limitations, acknowledging areas for potential enhancement and reflecting on emergent questions from the research process.

First, a significant limitation encountered in the quantitative aspect of the study was its reliance on secondary data as inputs for the MFA model built for Study 1. This approach, necessitated by the global scope of the study and the informal nature of the secondary copper market, could potentially limit the accuracy of the findings. Dedicating efforts to collect primary data on primary resource production, as well as recycling and EoL collection rates, possibly through industry collaborations or targeted surveys, might have yielded more current and context-specific insights and have improved the quantitative model's accuracy and relevance. However, given the financial and time constraints of this research project, it was not possible to explore these avenues further. Nonetheless, this limitation underscores the need for more comprehensive and regularly updated datasets on global material flows and specifically,

better data on EoL collection and recycling – without which it will be significantly more difficult to make policy or business decisions that promote the adoption of CE strategies and practices.

Secondly, while providing deep insights into the Chilean context, the qualitative study was limited in its geographical scope. Although the focus on Chile allowed for an intensive exploration of one specific mining context, this focus may restrict the generalisability of the findings to other resource-dependent regions. A comparative approach encompassing additional in-depth country case studies could have broadened the perspective on CE adoption across the global mining industry. For instance, preliminary investigations in Brazil indicated a substantial interest in CE initiatives that were unclear before the short field trip, hinting that a more thorough comparative study there might have provided valuable insights. However, I had only planned enough time for one site visit in Brazil, which did not allow me to explore this potential approach further.

Thirdly, the qualitative study faced limitations regarding access to communities, primarily due to language constraints – my Spanish and Portuguese were not strong enough to conduct interviews in languages other than English. This logistical challenge restricted the breadth of community engagement and potentially the depth of insights into local perspectives on CE practices. Future research could benefit from incorporating multilingual research teams or employing translation services to facilitate broader community access and engagement. This enhancement would enable a more inclusive understanding of the challenges and opportunities of CE adoption in the mining sector from a broader range of stakeholder perspectives.

Another encountered limitation was the potential for elite bias in the interview data, stemming from the focus on interviews with business leaders, government officials, and academics. While these interviews offered valuable insider perspectives, they may not fully

capture the diverse views of other stakeholders, such as local communities or lower-level employees in mining operations. Expanding the range of interviewees to include these groups could provide a more comprehensive view of the CE landscape in the mining sector and resource-dependent regions. Finally, integrating quantitative surveys with qualitative interviews might have offered a richer dataset, facilitated data triangulation, and potentially revealed broader CE implementation trends.

4. The limitations of end-of-life copper recycling and its implications for the circular economy of metals

Authors

Konstantin Born & Mehmet Metehan Ciftci

Spotlight

- The acceleration of the energy transition will lead to rapidly increasing demand for metals, such as copper.
- Recycling strategies will at most only be able to supply 50% of the total copper demand by 2050.
- We develop a novel material flow analysis (MFA) approach to test the potential of recycling strategies to meet future metal demand.
- Recycling is only one of the various circular economy strategies that are needed to reduce primary metal extraction.
- A stronger focus on developing circular economy strategies for mining production systems is needed.

Abstract

Increasing the recycling of metals reaching their end-of-life (EoL) is a vital circular economy approach to meet the growing demand for metals and reduce reliance on mining. To assess the potential of recycling strategies in fulfilling future metal demand and replacing primary production, we develop a novel dynamic probabilistic material flow analysis (MFA) model. Unlike previous MFA studies, our model explicitly explores the potential of recycling to reduce metal mining activities while considering uncertainties in future EoL collection and recycling rates. Focusing on copper, a critical mineral for low-carbon technologies, the model dynamically estimates the future copper stocks and flows under three different demand scenarios and probabilistic EoL collection and recycling assumptions. Our analysis reveals that the share of EoL secondary supply of overall copper demand, which currently stands at 23%, will even under the scenario with the lowest future copper demand only be averaging 33.4% over the next three decades. In addition, even under the most optimistic circumstances with lower than expected copper demand and very high collection and recycling rate growth, the annual share of EoL secondary supply of overall copper demand would only reach 49.6% in 2050. Thus, primary copper extraction is expected to rise significantly until at least 2040 and under 87% of all 30,000 modelled outcomes, primary production of copper in 2050 will still be above 2020 production levels. Consequently, we emphasise the need for alternative circular

economy strategies beyond recycling, such as demand reduction and mitigating the harmful impacts of primary metal production.

Keywords: Circular economy (CE), End-of-life recycling, Critical Minerals, Metals, Copper, Material flow analysis (MFA)

1. Introduction

There is growing evidence that the accelerating efforts to decarbonise economies globally will lead to rapidly increasing demand for many key metals (Hund et al., 2020; IEA, 2021; Seck et al., 2020; Simas et al., 2022; Watari et al., 2019). One often-invoked solution to fulfil the growing demand for metals while simultaneously decelerating the primary extraction of these materials is to move towards a so-called circular economy (CE) (Zink and Geyer, 2017). Although there are over 200 definitions of the CE concept (Kirchherr et al., 2023), the CE can be broadly understood as a transformative approach towards sustainable resource use within planetary boundaries that promises to "slow, narrow and close socioeconomic material cycles by retaining value as long as possible, thereby minimizing primary resource use, waste and emissions" (Haas et al., 2020, p. 1).

The CE concept began to receive significant scholarly attention in the early 2000s in the wake of the growth of new approaches to study industrial systems, such as industrial ecology and industrial symbiosis (Blomsma and Brennan, 2017; Ghisellini et al., 2016). By the late 2000s, the concept of the CE began to also receive attention from policymakers in China (People's Republic of China, 2008) and Europe (European Commission, 2015). One of the most prominent areas of focus in the scholarship of the CE since then has been metals (Merli et al., 2018). This is not surprising, as metals, unlike many other raw materials, do not lose their intrinsic properties during recycling and can be re-used multiple times without losing their quality or functionality (Hagelüken et al., 2016). However, the majority of research and policy efforts to develop and promote CE strategies to meet the growing demand for metals and other

material inputs have predominately focused on the potential offered by recycling materials found in products that have reached their end-of-life (EoL) (Ragossnig and Schneider, 2019; Schöggl et al., 2020).

The predominant focus on the EoL recycling of metal containing products in the CE literature and policy space has unarguably provided important contributions to the design and implementation of new recycling technologies, business models and other activities aimed at reducing primary metal production. However, there are growing questions whether increased EoL recycling efforts alone will be able to cover the expected increases in demand for many metals driven by growing populations, increased incomes and the significantly higher material intensity of low-carbon technologies (Dong et al., 2019; Reuter et al., 2013; Simas et al., 2022; Valero et al., 2018). To highlight the scale of the anticipated demand increases, Watari et al. (2021) reviewed 70 studies that forecast metal demand. They find that demand for all major metals is likely to increase continuously until 2050 with the demand for aluminium (215%), copper (140%), nickel (140%) and iron (86%) forecasted to grow significantly relative to demand in 2010. While many studies have been published on metal demand dynamics, very few studies have explicitly tackled the question of how much of this forecasted demand growth for metals can be met by recycling existing metal stocks.

Given the current scholarly focus on EoL recycling as the core CE strategy, it is essential to develop an evidence-based understanding of the potential secondary supply that can be unlocked by increasing the recycling of the in-use stock of metals at the end of their lifetime and the associated demand reduction for mined primary metals that can be achieved as a result. Even though there has been a lack of attention on estimating the potential of recycling to meet future metal demand, a few studies in recent years have at least included secondary supply forecasts in their analysis (e.g. Elshkaki et al., 2016; Gregoir & van Acker, 2022; Sverdrup et al., 2015; Watari et al., 2019). However, these studies do not explicitly investigate

the potential of recycling to meet the growing metal demand and do not account for the large uncertainties in future EoL collection and recycling rates. As a result, existing studies give limited guidance on the effectiveness of recycling strategies to generate sufficient secondary supply to meet future metal demand and therefore have limited explanatory power to assess the potential of recycling to reduce the need for increased primary mineral and metal extraction.

The goal of this paper is to fill this gap by using Material Flow Analysis (MFA) to explore the potential of EoL recycling to meet future metal demand. We build on previous work that combines a dynamic MFA approach with probabilistic forecasting to develop a new methodological approach that can estimate the future scale of recycled metals availability under uncertain EoL recycling performance and demand pathways. We then apply this new method to the global copper cycle. Based on this analysis, we discuss the implications of our findings before identifying several leverage points for research and policy to generate a more realistic understanding of the role that EoL recycling can play in meeting the growing demand for minerals and metals. We conclude with ideas for a future research agenda that includes a stronger focus on developing CE strategies for the production systems of primary metal production.

2. Materials and Methods

2.1. Material Flow Analysis

One of the well-known methodologies to quantify resource flows and understand the availability of anthropogenic stock of metalliferous materials is Material Flow Analysis (MFA) (Brunner and Rechberger, 2016). All MFA studies are based on the paradigm of industrial metabolism and use the methodological principle of mass balancing (Bringezu and Moriguchi, 2003). Despite this common foundation, MFA studies use a large range of differing methodological approaches and temporal scales (Graedel, 2019). While static MFA models

with a fixed timescale of one or several years used to be the norm, various methods to dynamically model past and future stocks and flows of metals have become well-established since the early 2000s (Müller et al., 2014). In contrast to static models, dynamic MFA models not only provide a snapshot of metal cycles at one point in time, but they provide information about the behaviour of a system over time.

In a parallel development in MFA studies, it has become more common to add probabilistic elements to MFA models in order to overcome the problem of uncertain modelling inputs (Laner et al., 2014). Probabilistic approaches have been used in previous MFA studies to control the uncertainty created by data availability limitations for key model inputs (e.g. Chen et al., 2023; Gottschalk et al., 2010; Song et al., 2017; Thiébaud et al., 2018).

In recent years, scholars have started to combine these two approaches into a new approach known as dynamic probabilistic MFA (DP-MFA) (Bornhöft et al., 2016). DP-MFA approaches have been used to forecast future stocks and flows of various resources, such as urban housing stock in China (Cao et al., 2018), engineered nanomaterials (Sun et al., 2017) and rubber release from tires (Sieber et al., 2020). However, despite a growing understanding that adding probabilistic elements to dynamic MFA models can help to overcome inherent uncertainties in forecasting future material stock and flow dynamics (Bornhöft et al., 2016; Müller et al., 2014), there have so far been no studies that use a DP-MFA approach to analyse future metal cycles in the context of the rapidly growing demand for certain metals driven by the energy transition.

While a number of recent studies that attempt to forecast future metal cycles and secondary metal supply have used either dynamic MFA approaches in tandem with various scenarios for future metal demand (Baars et al., 2021; Henckens, 2021; Gregoir and van Acker, 2022; Henckens and Worrell, 2020; Simas et al., 2022; Watari et al., 2022) or other non-MFA

approaches (Blagoeva et al., 2016; Dominish et al., 2019; Rizos and Righetti, 2022), all of these studies use deterministic point estimates in their modelling assumptions. This approach has a number of drawbacks. First, deterministic approaches can perpetuate inaccuracies in historic metal recycling data, potentially resulting in biased or unreliable predictions. Second, many MFA papers rely on historical extrapolation or overly optimistic assumptions regarding future metal demand and recycling rates, which can lead to an overemphasis on past experiences and neglect the feasibility of recycling assumptions.

In contrast, a dynamic probabilistic DP-MFA approach can allow for a more comprehensive and realistic treatment of uncertainties. Rather than relying on fixed point estimates, DP-MFA incorporates probabilistic elements that account for the uncertainty surrounding historical data and future projections. It can thus consider a range of possible outcomes for future metal demand, and EoL collection and recycling rates with distributional parameters based on realistic best estimates from academic studies. This provides a more nuanced view of the future metal cycles and secondary supply availability. By developing a DP-MFA model of the global copper cycle that can better account for the large uncertainties of historic metal use, future metal demand and EoL collection and recycling, this paper attempts to improve the insights from previous studies and aims to demonstrate the usefulness of adding probabilistic elements to dynamic MFA studies on future metals cycles and the forecasting of secondary supply availability of metals.

2.2. Case study: copper

There are several reasons why we selected the global copper cycle to test our modelling approach. Firstly, copper's widespread use across various sectors (Carrara et al., 2020; Hund et al., 2020) and its efficient and affordable conductivity (CDA, 2023) make it an indispensable component of the ongoing energy transition. Secondly, even before the energy transition, the common usage of copper has resulted in a substantial recyclable metal stock. Thirdly, the

existence of an extensive literature on copper supply and demand modelling, coupled with the availability of historic data[5], allows for the development of more accurate modelling assumptions and inputs. These factors position copper as an ideal case for testing and validating our modelling methodology, while also allowing us to draw more generalisable conclusions for future research on CE strategies.

2.3. Overview and design concepts of the model

The general principles underpinning this model are based on the dynamic probabilistic material flow analysis (DP-MFA) modelling approach (Bornhöft et al., 2016; Müller et al., 2014; Sun et al., 2017). Table 4.1 summarises the design concepts used.

[5] A wide range of industrial (see e.g., Copper Alliance, 2022; ICSG, 2022) and academic data (see e.g., Ciacci et al., 2020; Glöser et al., 2013; Henckens & Worrell, 2020; Schipper et al., 2018; Watari et al., 2019, 2022; Wiedenhofer et al., 2019) is available for copper covering collection rates, product groups in which copper has been used and many other key data required for a comprehensive MFA.

Overview	Purpose	Understanding the pathways of copper in the anthroposphere with a focus on evaluating future scenarios of secondary copper availability
	Materials (goods, substances)	Copper (17 product groups)
	Processes	Whole life-cycle of copper (Primary production and refining, fabrication, use, waste management, losses to the environment)
	Spatial and temporal scale and extent	Global, 1910 to 2050
	System overview	Simplified open-cycle loop
Design concepts	Basic principles	Dynamic probabilistic, top-down, retrospective and prospective
	Modelling approach (static, dynamic)	Inflow-driven dynamic stock modelling for annual cohorts
	Dissipation	Dissipative processes are explicitly deducted from each cohort
	Spatial dimension	Global system boundary
	Uncertainty	Mix of scenario-based (3 demand scenarios) and probabilistic (product lifetimes, future EoL collection and recycling processing efficiency rates) uncertainty considerations. Parameter uncertainty from literature. Model output uncertainty quantified via Monte-Carlo Simulations. Validation of results against available literature and via mass-balances. Sensitivity assessments via several one-at-a-time tests and visual inspection of model behaviour.

Table 4.1: Principles and concepts used for the model, based on and adapted version of the MFA ODD protocol developed by Müller et al. (2014)

The model has two stages, which both employ a DP-MFA approach. The first stage estimates past copper stocks and flows. In the second stage, the model dynamically estimates the future copper stocks and flows under three different copper demand scenarios and probabilistic EoL copper collection and recycling assumptions. Figure 4.1 shows the conceptual framework of the modelling process.

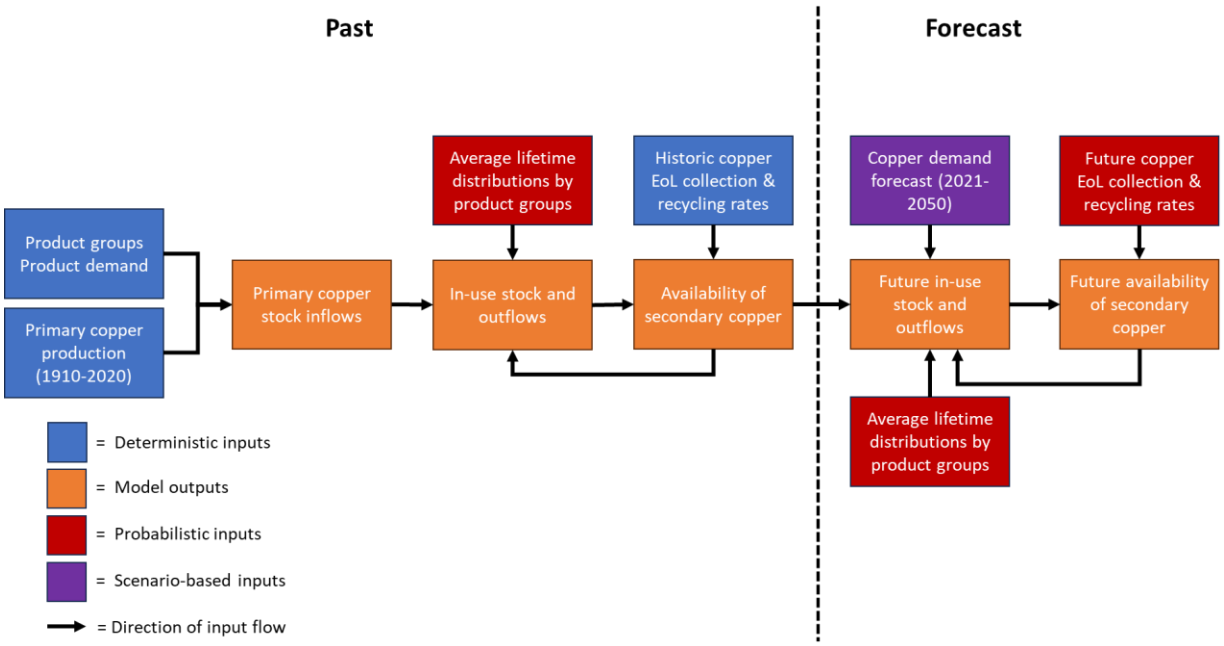


Figure 4.1: Conceptual framework of the modelling process

2.4. Copper stocks-and-flow model

2.4.1. Stage 1: Modelling the historic copper cycle

The foundation of the analysis in this paper is a top-down global open-cycle dynamic stocks-and-flow model (Müller et al., 2014) that estimates historic copper flows and stock levels from 1910 onwards. The model comprises five conceptual 'life stages' or 'cycles':

1) Primary production and refining
2) Fabrication
3) Use
4) Waste management
5) Losses to the environment

Using the principles of the law of mass conversion, the various 'life stages' are expressed in a simplified system (Figure 4.2).

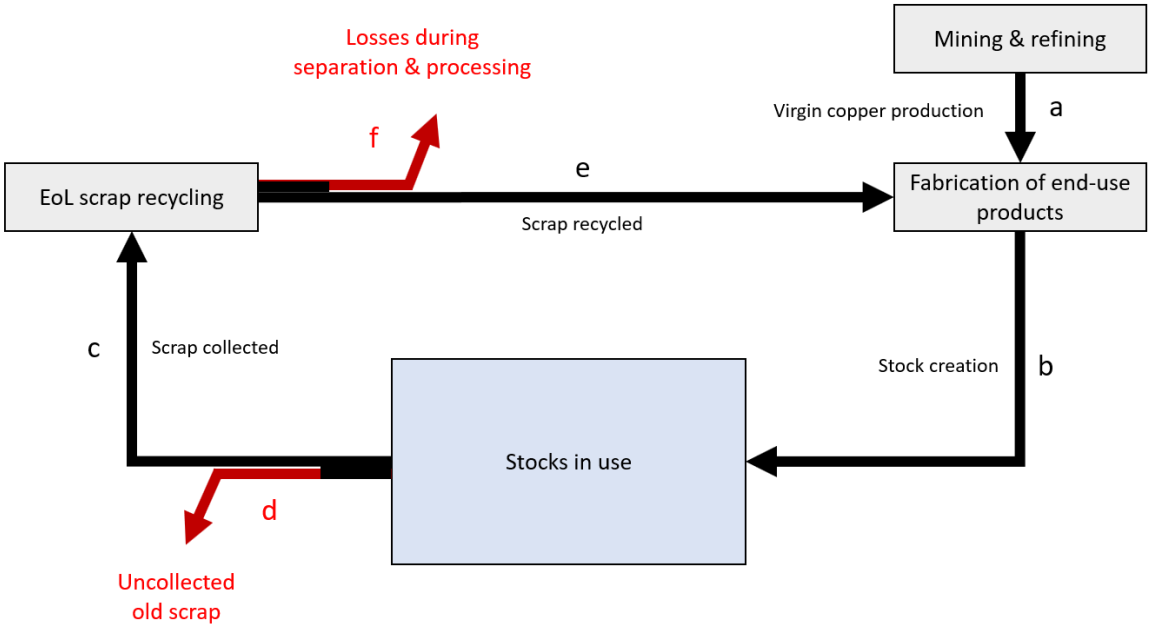


Figure 4.2: Global copper stocks and flows model. Arrows and letters represent the flows and boxes indicate the processes. Note that 'Stocks in use' include the cumulative sum of all the stock created until a given time (see Box S1.1in the SI for more information).

The model follows each tonne of copper starting with primary production through to the fabrication of 17 different end-use product groups that contain copper. After fabrication, the copper contained in these products enters its use phase and remains there for different periods of time depending on each product group's average lifetime. Using a time-cohort approach, the annual inflows to the anthropogenic copper stock is calculated by subtracting the outflow of embedded products that reach the end of their lifetime from the sum of the inflows of copper embedded in newly produced products and the copper embedded in previously produced products that are still in use. After leaving the use phase, the copper contained in these products is considered scrap and may be collected and recycled, thereby re-entering the cycle alongside primary copper, or it may be lost to landfills or in the processing waste of other metal cycles.

The global scope of this study and the informal nature of the secondary copper market makes the collection of primary data for model inputs challenging. As a result, all model inputs

are based on data from previously published studies. Data on the historic production of copper ores, refined production, historic EoL collection rates, EoL recycling processing efficiency rates, product group allocation and in-use stock residence times is taken from Glöser et al. (2013), the International Copper Study Group (ICSG) (2022, 2019, 2018, 2015, 2014) and the International Wrought Copper Council (IWCC) (2022). Although many studies use average in-use stock residence times, we use normally distributed residence times following Glöser et al. (2013), as accurate data on stock residence time is very hard to gather and therefore inherently uncertain (Eckelman and Daigo, 2008; Gorman and Dzombak, 2020; Wang et al., 2017). A detailed description of the model underlying this work, including the input data, data sources, and all relevant equations can be found in sections S1 to S3 of the *Supplementary Information (SI)*.

2.4.2. Stage 2: Modelling the future copper cycle

The second stage of the model estimates the future stocks and flows of the copper cycle. In order to account for the uncertainties in future copper demand, EoL collection rates, and EoL recycling processing efficiency rates, the second stage of the model uses a blend of probabilistic forecasting and dynamic scenarios.

2.4.2.1 Future metal demand

Future demand for metals is inherently uncertain and there are a number of different ways to model this uncertainty. We chose to use scenarios to account for this uncertainty for two reasons. First, it is difficult to define probability parameters for future demand outcomes. Second, scenario-based modelling allows for results analysis with greater explanatory power than probabilistic approaches given the wide range of demand forecasts, which would produce results with very large error margins. As a result, the future copper demand in this model is based on three distinct future material demand scenarios for a range of minerals critical for the energy transition developed by the IEA (2021): (1) Stated Policies Scenario (STEPS), (2)

Announced Pledges Scenario (APS), and the Net Zero Emissions by 2050 Scenario (NZE) (Table S2.2 in the SI explains the demand scenarios in more depth).

The choice to use the IEA's scenarios was made because we wanted to use demand scenarios for multiple warming pathways that have been derived bottom-up from estimated future use of copper applications, as we believe that this accounts better for ongoing changes in material intensity of technologies and the impact of technology deployment speed on absolute material demand. In contrast, most other metal demand forecasts only provide forecasts for one specific climate warming scenario and often use a top-down approach that extrapolates past material intensity and resource use dynamics into the future[6]. Although the IEA's projections do use relatively conservative technology adoption rates and only account for limited material efficiency gains, its recent publication date, the availability of three different demand scenarios with varying warming potential based on the same methodology, and its wide use in policy circles make their use a good choice.

2.4.2.2 Future end-of-life collection and recycling

We take a different path to account for the inherent uncertainty in the future EoL recycling of copper containing products. Instead of using scenarios, we employ probabilistic methods to forecast the growth rate of two key EoL recycling indicators: the EoL collection rate and the EoL recycling processing efficiency rate. We chose this approach for two key reasons. First, due to the informal nature of metal recycling activities in many parts of the world, even current recycling data has large error margins (Reuter et al., 2013). Second, there are studies that estimate achievable future recycling rates for copper (e.g., Ciacci et al., 2017; Watari et al., 2019; Abdelbaky et al., 2021; Rizos & Righetti, 2022), which makes it possible to derive appropriate parameters for probability distributions.

[6] See Watari et al. (2022) for a good overview of recent demand forecast studies on copper.

Given the sparse data availability on previous EoL collection rate increases, we chose a normally distributed linear growth rate to simulate the future EoL collection rates. Linear increases are widely used in the literature (e.g. Ciacci et al., 2017; Henckens, 2021; Schipper et al., 2018). The parameters of the distributions are based on the literature (Table S2.2 in the *SI*).

2.4.2.3 Uncertainty quantification

We used Monte Carlo uncertainty analysis to quantify the uncertainties in our results. We ran 10,000 simulations for each of the three demand scenarios using the software @Risk. Each simulation uses a different combination of product group lifetime distributions, EoL collection and EoL recycling processing efficiency growth rates.

2.5. Methodological limitations

The model does not attempt to capture the full complexity of the copper life cycle as done in previous work on global copper stocks and flows (e.g. Graedel et al., 2004, 2011; Glöser, Soulier and Tercero Espinoza, 2013; Ciacci, Vassura and Passarini, 2017). It is rather an attempt to build a simplified, but robust model that allows us to simulate the future availability of recycled copper supply in relation to the expected demand for copper under different collection, recycling processing efficiency and demand scenarios.

The model therefore makes a number of simplifying assumptions**.** Most importantly, it does not account for stocks and flows of new scrap[7], as the vast majority of it is reused immediately in the fabrication process (Glöser et al., 2013). Therefore, new scrap does not act as a demand substitute for primary production and can be ignored for the purpose of this study. We also make other simplifying assumptions regarding scrap stocks, product groups and residence times, the economics of copper recycling and copper prices, future copper supply

[7] New scrap is the waste that is produced during the fabrication process.

dynamics, as well as policy changes. A more detailed explanation of the methodological limitations can be found in S3 of the *SI*.

3. Results

3.1. Global in-use copper stocks and outflows

The global annual primary copper production has increased from 0.85 million metric tonnes (Mt) in 1910 to more than 20 Mt in 2020. Due to its durable nature, a significant part of the cumulative copper production is still in use today, either because it is still resident in the technosphere for the first time or because it has been recycled one or more times. The size of this in-use stock and the flows from this stock into the global waste management system are the key determinants of the potential for future secondary supply production.

We find that the in-use stock of copper has grown rapidly over the past century. While it was only around 60 Mt in 1960, we estimate that it has grown to over 460 Mt in 2020 (Figure 4.3). We further estimate that 29% of this in-use stock has already been recycled at least once. However, more than 100 Mt of copper that reached the end of its life have also been lost to landfills, non-functional recycling or have been abandoned in place since 1910. We back tested the validity of these results and our historic model inputs by comparing the estimated in-use stock with the existing scientific literature. The results showed that our findings are within a margin of error of less than 4% of two comparable studies (Figure S1 in the *SI*).

The in-use stock will continue to grow in the coming years. We estimate that the in-use copper stock will increase by between 150 and 290 Mt by 2040. Even under the most conservative STEPS scenario, the in-use stock of copper has the highest likelihood to reach ca. 650 Mt in 2040, which represents a 41% increase compared to 2020 stock levels (Figure 4.4). While in-use stock will rise rapidly, so will the outflows of copper containing products that reach the end of their life. In-use stock outflows will rise from ca 16 Mt per annum in 2020 to

a range of between 30 Mt per annum (STEPS) and 33Mt per annum (NZE) in 2050 (Figure 4.5). However, contrary to the future increase in in-use stock where we can observe a significant difference between the outcomes of the three demand scenarios, the difference between the three demand scenarios is much less pronounced when it comes to stock outflows.

The main reason for this is the long in-use residence time of copper containing products. It takes 23 years on average for a tonne of in-use copper to reach the end of its life. Accordingly, a tonne of copper that reaches the end of its life today will on average have been processed and fabricated around the last millennium. Since then, primary copper production has grown from ca. 13 Mt per annum to more than 20 Mt per annum today. Similarly, a tonne of copper that reaches the end of its life in 2040 will have on average been processed and fabricated in 2017. Accordingly, most of the in-use stock outflows by 2040 are driven by past production of copper. As a result, future production growth of copper containing products driven by the energy transition only has a relatively small impact on stock outflows until the mid- to late-2040s.

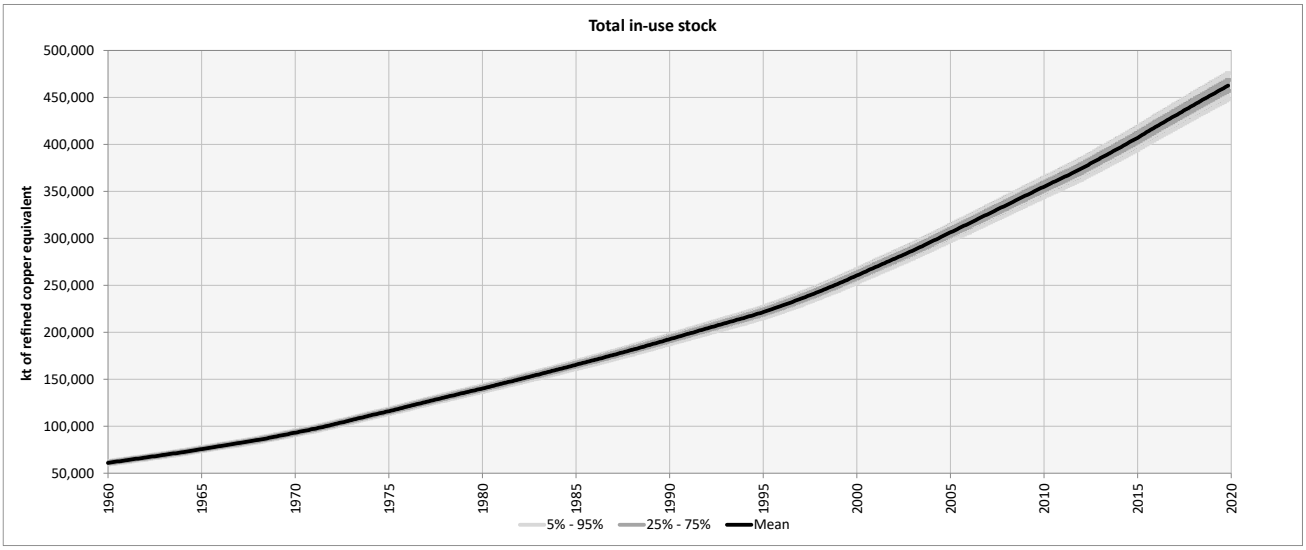


Figure 4.3: Evolution of the historic in-use stock of copper (1960-2020)

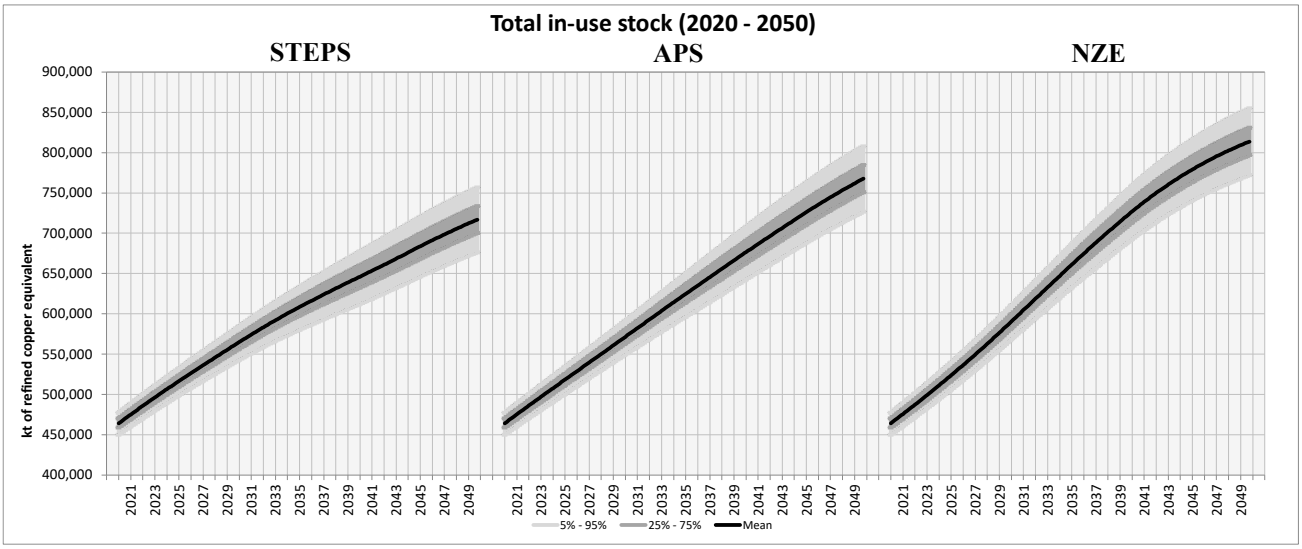


Figure 4.4: Total in-use stock of copper under each of the three IEA scenarios (2020 to 2050)

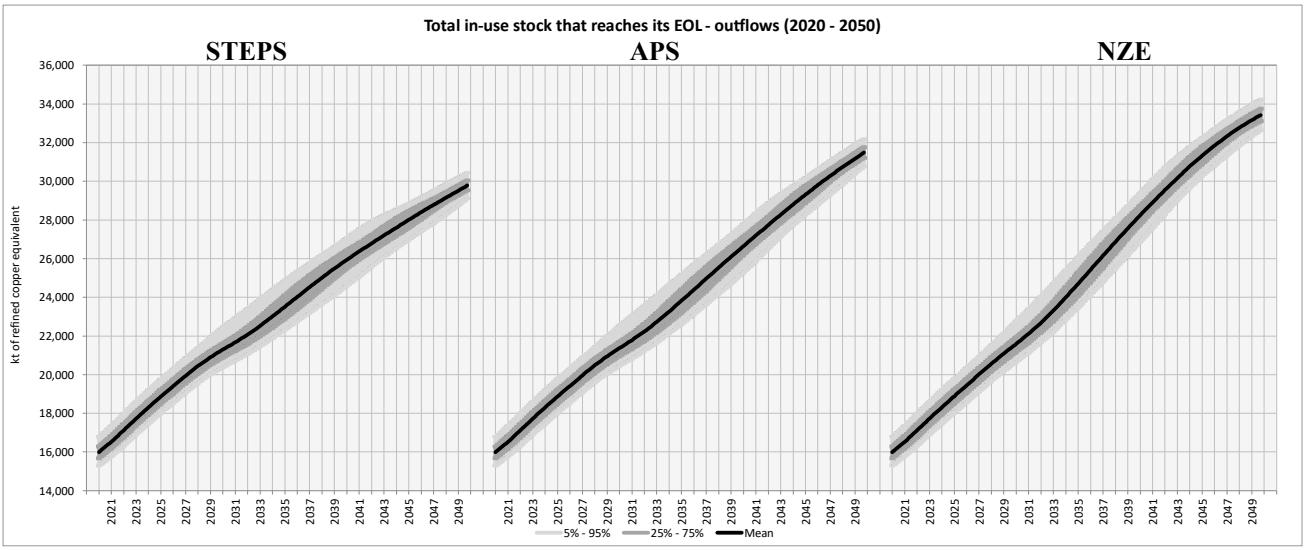


Figure 4.5: Total in-use stock of copper that reaches its end-of-life under each of the three IEA (2020 to 2050)

3.2. Evolution of secondary copper availability

As the outflow of in-use stock determines the availability of scrap material, a similar dynamic can be observed when it comes to the growth of the secondary copper supply. Even under the very strongly front-loaded future demand growth of the NZE scenario, annual production of secondary supply will only be ca. 10% higher than under the most modest demand growth estimates of the STEPS scenario (Figure 4.6). Nonetheless, the secondary supply of copper will grow significantly under all scenarios. Annual production of secondary copper will at least double from around 6 Mt in 2020 to over 15 Mt by 2040 due to an average annual growth rate

of secondary supply of 2.9% (STEPS), 3.1% (APS) and 3.3% (NZE). All scenarios follow a similar growth trajectory with a peak in secondary supply growth in the first half of the 2020s, before falling off thereafter (Figure 4.8). This dynamic can be explained by unprecedented relative growth in primary copper production in the latter half of the 1990s of over 5% per annum (USGS, 2015), statistical base effects and limits imposed by the finite amount of copper products that reach the end of their life each year. As a result of this steady growth, the annual share of secondary copper that will be available to meet overall copper demand will increase steadily for all scenarios until 2050 (Figure 4.7 & 4.9).

The results of our analysis show that the share of EoL secondary supply of overall copper demand, which currently stands at 23% will even under the scenario with the lowest demand (STEPS) only average 33.4% over the next three decades. The lowest average share would be achieved under the NZE scenario where 31% of total copper demand between 2021 and 2050 would be supplied by secondary material. The key determinants that explain the differences in outcomes are the amount of demand increases and the timing of demand growth. While larger overall demand increases lower the share of secondary supply, quicker demand increases lead to a faster growth in in-use stock and larger stock outflows in the 2040s.

Peak annual copper demand over the next 30 years is projected to be 36% (STEPS), 48% (APS) and 52% (NZE) higher than current annual demand. Although the STEPS scenario has the lowest demand growth rate of the three scenarios, it also has the lowest absolute demand increases and thus displays the highest average share of secondary material over the coming three decades. However, as a consequence of the higher total demand for copper and subsequent higher growth in primary production and in-use stock inflows under the NZE scenario, by 2050 the NZE scenario displays the highest annual share of total copper demand supplied by recycled material (Figure 4.7). But even under the most optimistic circumstances of the NZE scenarios with very high collection and recycling rate growth (95th percentile

outcome), the annual share of EoL secondary supply of overall copper demand would only reach 49.6%.

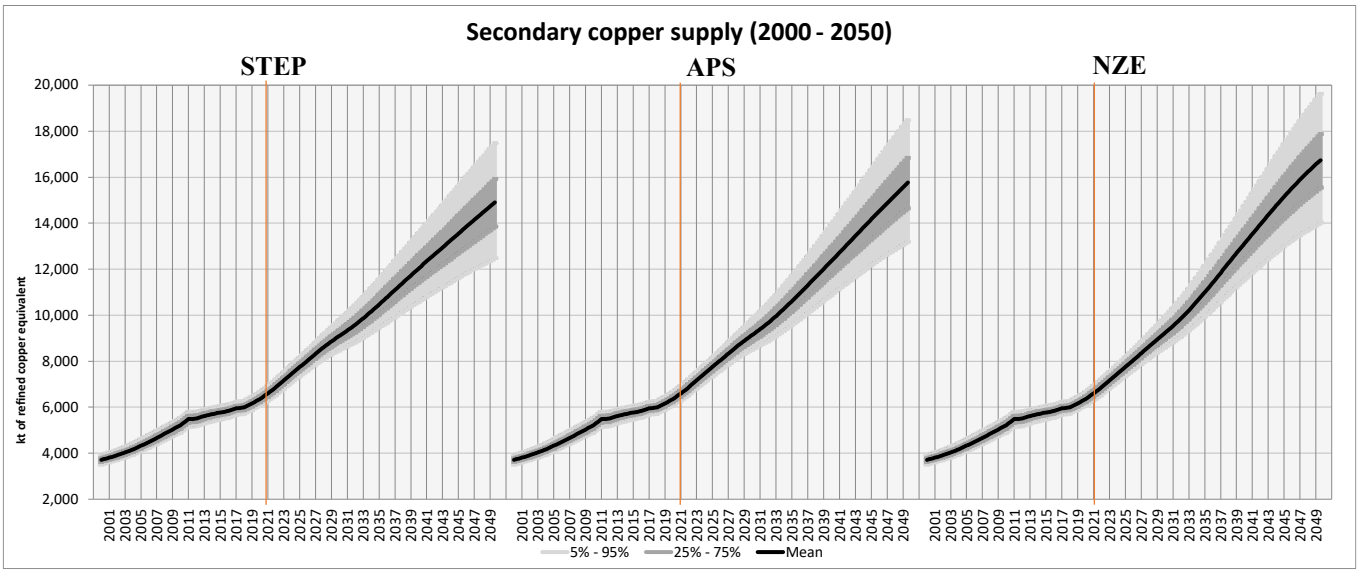


Figure 4.6: Volume of secondary copper supply under each of the three IEA demand scenarios (2000 -2050). Red line = forecast

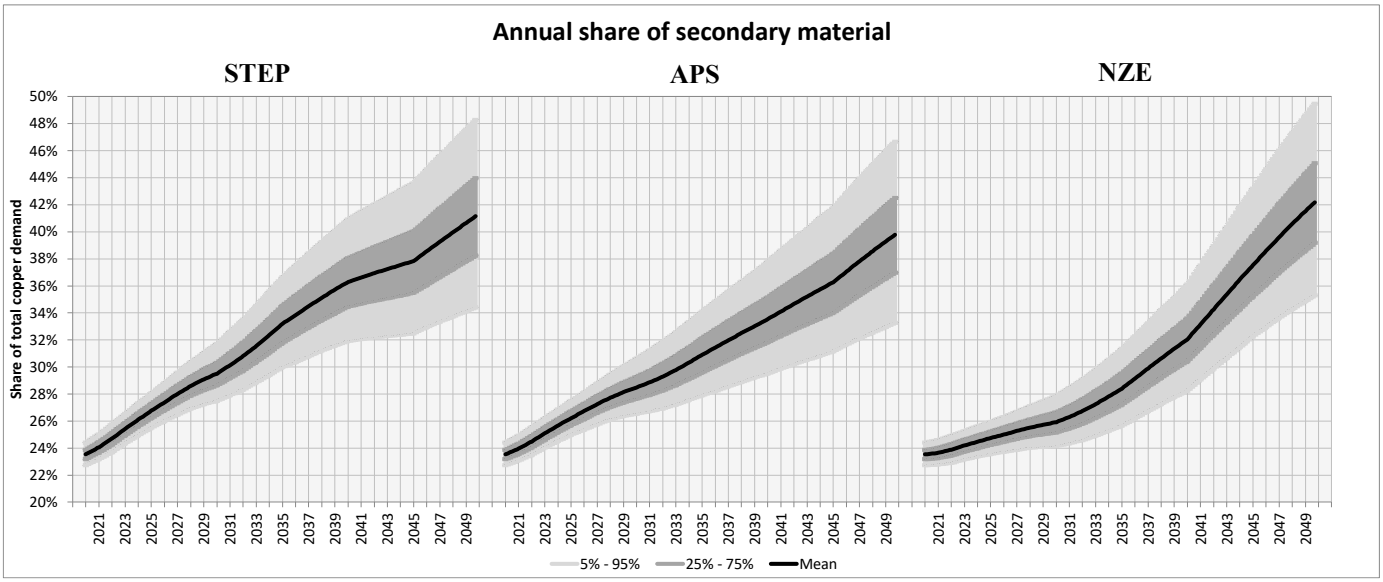


Figure 4.7: Annual share of total copper demand supplied by recycled material under the three IEA scenarios (2020 to 2050)

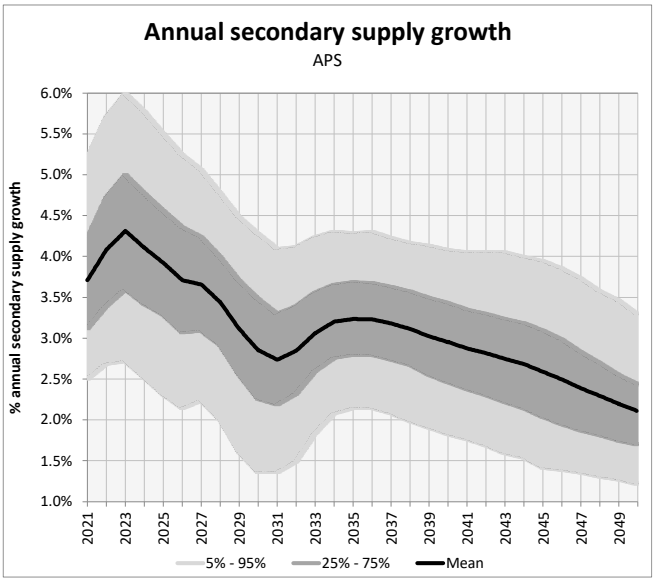


Figure 4.8: Future annual recycled material growth rate under the APS scenario (2021 – 2050)

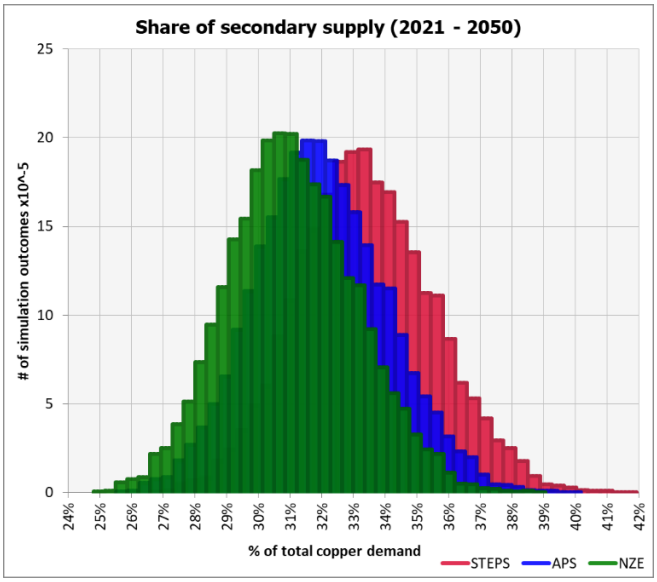


Figure 4.9: Share of total copper demand supplied by secondary material (2021 – 2050)

3.3. Impacts on primary copper production

Thus, it becomes clear that despite rapidly growing volumes of secondary copper supply, large increases in the total demand for copper will not slow the need for primary copper production growth for some time to come. We find that under all demand pathways primary production will increase at least into the late 2020s (Figure 4.10). In addition, in 87% of modelled outcomes across all three scenarios, primary production of copper in 2050 will still be above 2020 production levels.

Under the APS and NZE scenarios, primary production will continue to grow until at least 2040. We can observe a reduction of primary production under STEPS in the 2030s before rebounding growth in the early 2040s, as total copper demand accelerates at its fastest pace from 2040 onwards in this scenario, while previously slower demand growth leads to smaller in-use stock outflows that are available for recycling. Only 28% of all modelled outcomes under the STEPS scenario would reduce primary production of copper in 2050 below 2020 levels, while under APS and NZE only 2.2% and 9% of modelled outcomes respectively would

meet this threshold. Therefore, only under the STEPS scenario might primary production be replaced sufficiently by secondary material to fall back to current production levels in 2050. All other scenarios will with great likelihood require higher primary copper production in 2050 than in 2020.

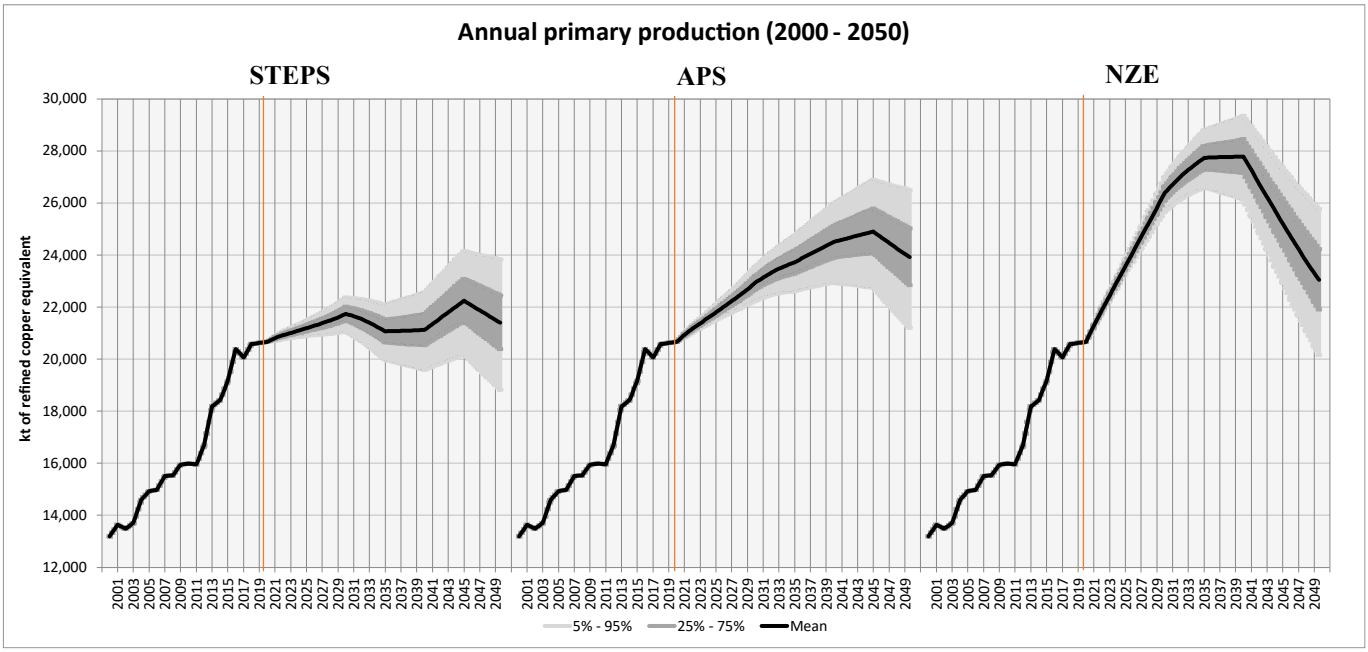


Figure 4.10: Volume of required primary copper extraction to fulfil demand under each of the three IEA demand scenarios (2000 -2050). The red line marks the start of the forecast period in 2021.

4. Discussion

Our dynamic forecast of the future global copper cycle illustrates the unique challenges that many countries and industries will face: how to meet the growing demand for metals while reducing their reliance on the extraction of primary metals. We find that recycling as a CE strategy, while important, is insufficient to decrease the demand for the primary extraction of copper before 2050 under all three demand scenarios we modelled. This suggests that although advances in recycling are essential if we are to reduce primary production of copper, our analysis shows that there is a less than 7.5% overall probability that the annual copper demand will be sufficiently met by additional recycling capacity to reduce primary copper production

compared to today's level by 2050. As a result, even with large advances in recycling technology and scrap collection efforts, dozens of new copper mines would have to be opened to increase primary metal extraction and replace the anticipated decreases in production from existing operations, as many large copper mines will reach the end of their useful life before 2050 and average copper ore grades continue to fall (Northey et al., 2014; Tabelin et al., 2021).

These findings are also not unique to copper. Considering the comparatively high recycling rate for copper and the substantial existing in-use stock, the inability of secondary supply to fully replace primary production for copper raises serious concerns for other critical minerals required for the energy transition, most of which have significantly lower existing in-use stocks and recycling capacity. It suggests that other energy transition minerals, such as lithium, will likely encounter even larger constraints, as despite their lower in-use residence times, very low existing in-use stock levels place a natural cap on EoL material that becomes available for recycling in the short-term. These insights therefore also have significant implications for the debates on the CE of metals and the supply security of minerals critical to the energy transition, as they raise serious questions regarding the adequacy of the currently predominant focus of CE strategies on EoL recycling. This is not to say that EoL recycling does not have an important part to play in transitioning metal supply chains towards more circular modes of production and consumption. However, EoL recycling should be seen as just one of various CE strategies and other CE strategies should receive heightened – if not equal – attention (Allwood, 2014).

There is growing evidence that despite the dominant focus on EoL recycling strategies, demand-side CE strategies, such as product lifetime extensions and changed consumption practices (e.g. sharing of electric vehicles and reduction in vehicle sizes), have the same or even greater potential to reduce primary resource demand than EoL recycling (Watari et al., 2022, 2021a). While this calls for a new effort to develop a suite of CE strategies and policies

that reduce demand for metals, the large increases in primary production of metals that we are likely to see in the coming decades points towards another important part of the metal life-cycle that can be leveraged to at least reduce the potential environmental and social impact of growing primary metal production: the application of CE strategies in the industrial extraction systems of primary metals.

In recent years the topics of resource governance and responsible sourcing of minerals have received renewed attention (Ali et al., 2017; Ayuk et al., 2020; Dominish et al., 2019; Sovacool et al., 2020; Watari et al., 2021c). While these are important debates given the historic failures of the mining industry to extract materials responsibly and to the benefit of host countries and communities (Lèbre et al., 2020), they take place in a silo that sits mostly outside the scholarship and policy efforts aimed at promoting CE approaches. This is arguably a lost opportunity, as the value proposition of the CE paradigm lies in its approach to offer a systems-solution framework that can promote more sustainable production and consumption practices and business models across industries and value chain segments. There is ample evidence of CE approaches being successfully applied to transform business models and production systems not just in mid- and downstream parts of global value chains, but also in the upstream production of raw materials (Ellen MacArthur Foundation, 2023). Therefore, to support industry and policy decision-makers, the research community must explore how CE thinking applies to mining production systems. This could include investigating existing CE approaches in mining, assessing policy readiness to incentivize CE adoption by mining companies, and adapting strategies from other sectors. Regional sharing of mining infrastructure and reusing mining waste products should also be considered to reduce extraction process waste.

To conclude, we have shown that in the case of copper, even under optimistic EoL recycling assumptions, primary production will continue to rise over the coming decades and will with very high likelihood still be above current levels by 2050. Further analysis on other

metals will be required to strengthen these insights, but our findings support the argument that in addition to ramping up EoL recycling efforts, a stronger focus must be placed on developing other CE strategies if we are to move towards more circular metal cycles in the short- to medium-term.

5. Application of circular economy approaches in the mining sector: evidence from Chile

Author

Konstantin Born

Abstract

This paper explores the application of Circular Economy (CE) approaches in the mining sector. Large-scale mining is essential for global material supply and the energy transition but poses significant environmental challenges. Applying CE approaches can help mitigate these challenges by reducing waste, improving resource efficiency, and minimising environmental impacts. However, the existing CE literature has been predominantly focused on downstream value chain segments, requiring additional conceptual tools to guide the application of CE approaches in upstream industries, such as the mining sector. The study advances the literature on CE, responsible sourcing of minerals and sustainable raw material extraction by identifying three conceptual elements that can help in the design and application of appropriate CE approaches in the mining sector: (1) a clear communication of the *goal and boundary* of the industrial production system that the adoption of CE practices is targeting; (2) an identification of the *source and type of inputs* used by the system; and (3) a consideration of the *resource state* of these inputs and the subsequent structural wastes generated from them. These new conceptual elements allow for a system-level analysis of CE adoption tailored to the context of the mining industry.

Using the case of Chile, the study demonstrates how these conceptual elements can be applied to map existing CE approaches used in the mining sector. Findings reveal that Chilean copper and lithium mining companies are successfully applying CE approaches, such as using seawater in ore processing, remining and repurposing tailings, and remanufacturing mining machinery. This shows that there is significant potential for the mining industry to apply CE thinking. However, the case study also highlights prevalent tendencies of a lack of systems thinking and additionality in the design of CE approaches, which present significant challenges for the sector to apply CE approaches at scale.

Keywords: Circular economy, mining, upstream industries, raw materials, responsible mining, sustainability, Chile

1. Introduction

Our current economic system continues to be heavily reliant on economic growth and the continuous expansion of industrial production. This has led to a steady rise in the material footprint of the world economy over the past century (Giljum, 2004; Hickel, 2019; Krausmann et al., 2009). The large-scale extraction activities underpinning this economic system have been shown to have significant negative social and environmental impacts that are increasingly subject to scrutiny and criticism (Lèbre et al., 2020; Watari et al., 2021c). For instance, it is estimated that primary mineral and metal production already accounted for approximately 10% of the total global energy-related greenhouse gas (GHG) emissions in 2018 and is rising further (Azadi et al., 2020; Greene, 2017). Mining also contributed to 7% of global deforestation and is the fourth-largest driver of forest habitat loss and its associated climate impact (World Bank, 2019). Mining's negative impact on biodiversity (Sonter et al., 2020) and its use of increasingly scarce freshwater resources (Tost et al., 2018) are also well documented.

One key approach in the search to tackle this issue is the circular economy (CE) concept. It proposes shifting our economic system from the current linear 'take-make-waste' model to a regenerative system that prioritises material efficiency and minimises waste (de Jesus and Mendonça, 2018; EMF, 2012). As a framework for sustainable production, the CE concept has seen significant growth in both the scholarly debate and the policy discourse in recent years (Kalmykova et al., 2018). Private companies are also increasingly exploring new business models and strategies based on CE principles (Hernández-Chea et al., 2021; Lüdeke-Freund et al., 2019).

However, while evidence suggests that CE approaches are crucial to reducing society's resource demands, they are insufficient to allow the cessation of primary resource extraction activities for various reasons (Bianchi and Cordella, 2023). On the one hand, existing stocks of

most mined raw materials are too small to cover the growing demands of global development and emerging technologies (IEA, 2021; Watari et al., 2019). In addition, many potential sources of metal stocks are held in use for extended periods (Haas et al., 2015; Watari et al., 2021b) and technological requirements for materials constantly evolve (Langkau and Tercero Espinoza, 2018), increasing the demand for mined raw materials. On the other hand, significant barriers remain in increasing collection rates and reducing recycling losses to reduce the amount of metals lost during each usage cycle (Charpentier Poncelet et al., 2022; Reuter et al., 2019). Consequently, extracting primary raw materials will remain indispensable to modern society's functioning for the foreseeable future.

Despite this evidence, mining and other raw material extraction activities situated in the *upstream* segments of global value chains have traditionally received significantly less attention in the CE literature than *downstream* value chains (Alcalde-Calonge et al., 2022; Merli et al., 2018). In light of the growing understanding of the need for continued primary material extraction, this paper argues that there is a need for a better empirical understanding of CE application in *upstream* industries more broadly, and critical energy transition mineral extraction systems more specifically. Furthermore, it posits that the CE concept, its principles, and associated strategies present a useful framework to improving the sustainability of raw material extraction systems themselves. Especially as there is increasing evidence that there are effective CE approaches that can be used to reduce large-scale mining's environmental footprint, material consumption and structural waste – from the reduction of freshwater use (Hamraoui et al., 2024; Jamett et al., 2022) to the repurposing of mine tailings as inputs for other industries (Kinnunen et al., 2022; Singh et al., 2020) and the remanufacturing of mining machinery (Cisternas et al., 2022).

However, the mining sector and other upstream raw material extraction activities have received comparatively less attention in circular economy (CE) research. Furthermore, the

mining sector arguably faces distinct complexities compared to downstream industries, making it essential to have tools that facilitate systematic assessments to identify targeted CE approaches that address their unique challenges. This paper argues that current CE literature requires additional conceptual elements to effectively develop and apply CE approaches in mining production systems. In particular, this paper hypothesises that there are three crucial conceptual elements that can help in the design and application of appropriate CE approaches in the mining sector: (1) a clear communication of the *goal and boundary* of the industrial production system that the application of CE approaches is targeting; (2) an identification of the *source and type of inputs* used by the system; and (3) a consideration of the *resource state* of these inputs and the subsequent structural wastes generated from them.

To demonstrate the usefulness of these conceptual elements, they are used to map and analyse the existing application of CE approaches in Chile's mining sector. The case study reveals that Chile's mining industry has begun to apply various CE approaches to improve material efficiency and reduce structural waste, such as reusing mining by-products in other industries and improving resource use efficiency. These include using seawater in mining processes to reduce freshwater consumption, remining and repurposing of tailings, and remanufacturing mining machinery.

The remainder of this paper is organised as follows: Section 2 discusses the materials and methods; Section 3 then outlines the theoretical background and existing gaps in understanding CE implementation in the mining sector and other upstream industries. Section 4 then introduces the new conceptual elements for CE implementation in the mining industry; before Section 5 presents the case study results from the Chilean mining sector. Section 6 discusses the results before Section 7 concludes the study with a summary of the key arguments.

2. Materials and Methods

Data collection for this paper was undertaken from January 2022 until May 2023. The study design entailed three components: (1) desk research, (2) semi-structured and focus group interviews with experts from the UK, Australia, Canada, South Africa, Chile and Brazil, and (3) coding and data analysis (see Figure 5.1).

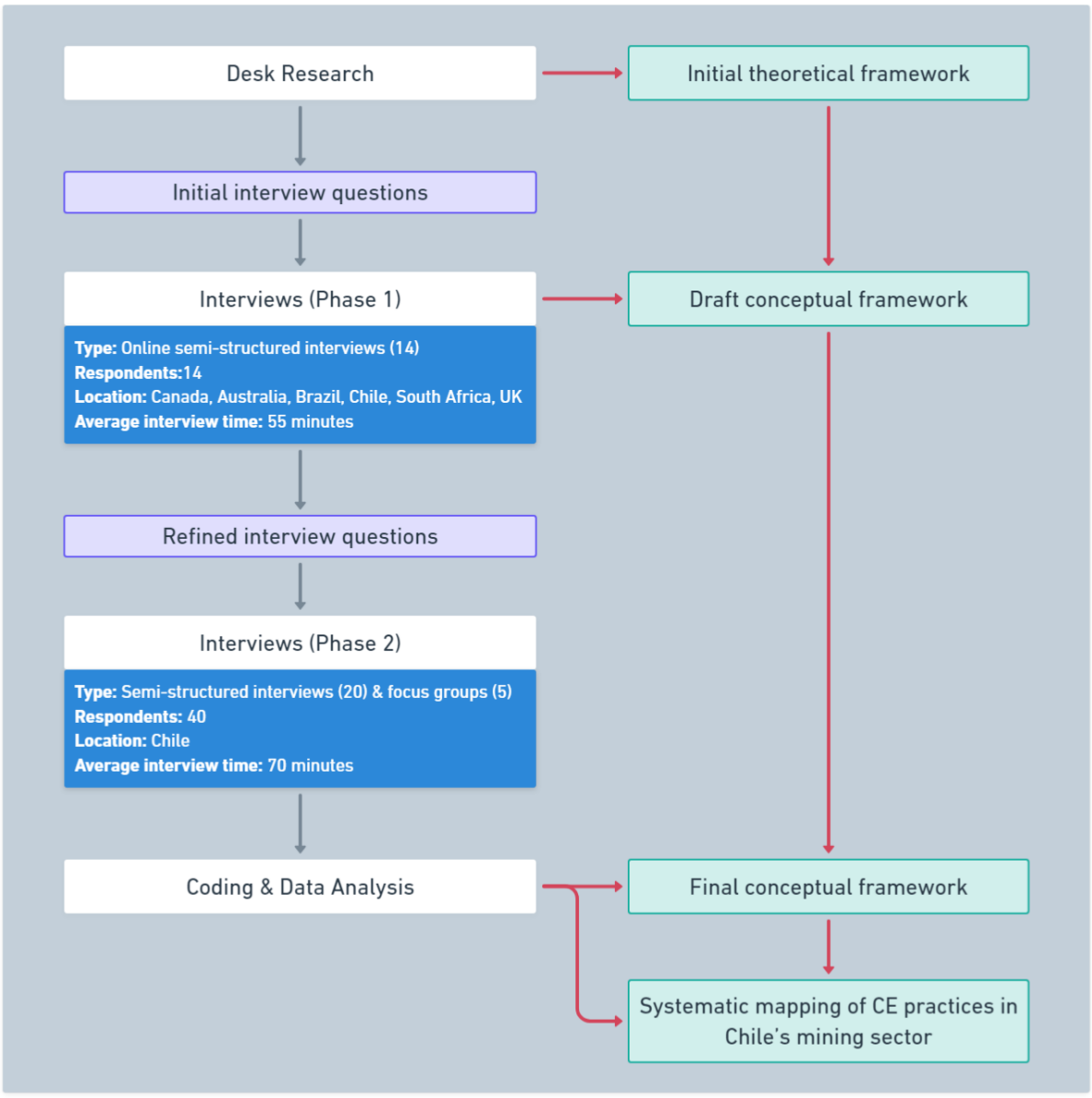


Figure 5.1: Study design

2.1. Desk research

Desk research started by carrying out searches in Thomson Reuters' Web of Science, Elsevier's Scopus, and Google Scholar with the keywords ‘circular economy’ in combination with several keywords related to mining and upstream industries (e.g. ‘mining’, ‘upstream industries’ and ‘raw materials’). Overall, more than 50 relevant studies were identified. I reviewed these to develop a foundational understanding of the current scholarly debate on CE implementation in ‘upstream’ industries and the broader role of this value chain segment in the macro-transition towards more circular production and consumption systems. Based on this, an initial theoretical framework and interview questions were developed.

2.2. Interviews

I then conducted 35 individual semi-structured interviews and five focus group interviews, interviewing experts from industry, policy and academia (see Table 5.1). I had initially intended to conduct only semi-structured interviews, but during the fieldwork, I came across some organisations that had several experts who were able to provide different perspectives on the research subject. However, some were too time-constrained to meet with me individually, so I conducted some interviews as focus groups instead.

The interviews focused predominantly on the perspectives of businesses and policy-makers since these are believed to be the key actors in CE implementation (Bocken et al., 2017; European Commission, 2014; Kirchherr et al., 2018). Moreover, the responses provided by policymakers and businesses offer a practical account of applying CE approaches from a practitioner's perspective. Due to practical reasons and confidentiality considerations, only 69% of these conversations were audio-recorded and transcribed. However, detailed interview notes were taken during all interviews.

#	Position	Organisation	Type	Interview type
Phase 1 - Global				
1	Manager (Sustainability)	Mining firm	Business	Semi-structured interview
2	CEO	Consultancy	Business	Semi-structured interview
3	Director (Innovation & Circular Economy)	Industry association	Business	Semi-structured interview
4	Manager (Circular Economy)	Mining firm	Business	Semi-structured interview
5	CEO	Consultancy	Business	Semi-structured interview
6	Director (Circular Economy)	Mining firm	Business	Semi-structured interview
7	Professor	University	Academia	Semi-structured interview
8	Professor	University	Academia	Semi-structured interview
9	Environmental Engineer	Mining firm	Business	Semi-structured interview
10	Manager (Mining)	Mining firm	Business	Semi-structured interview
11	Manager (Social)	Mining firm	Business	Semi-structured interview
12	Manager (Sustainability)	Mining firm	Business	Semi-structured interview
13	Manager (Environmental)	Mining firm	Business	Semi-structured interview
14	Manager (Innovation)	Mining firm	Business	Semi-structured interview
Phase 2 - Chile				
15	Executive Director	Supplier	Business	Semi-structured interview
16	Policy-maker	National government	Government	Focus group interview
17	Policy-maker	National government	Government	Focus group interview
18	Policy-maker	National government	Government	Focus group interview
19	Policy-maker	National government	Government	Focus group interview
20	Policy-maker	National government	Government	Focus group interview
21	CEO	Supplier	Business	Semi-structured interview
22	Programme Manager	Development agency	Government	Focus group interview
23	Programme Officer	Development agency	Government	Focus group interview
24	Programme Officer	Development agency	Government	Focus group interview
25	Board member	Mining firm	Business	Semi-structured interview
26	Director	Industry association	Business	Semi-structured interview
27	CEO	Industry association	Business	Semi-structured interview
28	Director	Consultancy	Business	Semi-structured interview
29	Professor	University	Academia	Semi-structured interview
30	Advisor (Technology and Market)	Mining firm	Business	Semi-structured interview
31	CEO	Public-private partnership	Business/ Government	Semi-structured interview
32	Project Leader (Mining)	National government	Government	Semi-structured interview
33	CEO	Supplier	Business	Semi-structured interview
34	Assistant Professor	University	Academia	Semi-structured interview
35	CEO	Public-private partnership	Business/ Government	Focus group interview
36	Director	Public-private partnership	Business/ Government	Focus group interview
37	Manager	Public-private partnership	Business/ Government	Focus group interview

#	Position	Organisation	Type	Interview type
38	Manager	Public-private partnership	Business/ Government	Focus group interview
39	Programme Manager	Development agency	Government	Semi-structured interview
40	Executive Director	Public-private partnership	Business/ Government	Semi-structured interview
41	Head of Sustainability	Mining firm	Business	Semi-structured interview
42	Programme Manager	Consultancy	Business	Semi-structured interview
43	President	Industry association	Business	Semi-structured interview
44	Executive Director	Research institute	Academia	Semi-structured interview
45	Country Director	Mining firm	Business	Semi-structured interview
46	Professor	University	Academia	Semi-structured interview
47	Manager (Sustainability)	Mining firm	Business	Focus group interview
48	Environmental Engineer	Mining firm	Business	Focus group interview
49	Environmental Engineer	Mining firm	Business	Focus group interview
50	Programme Manager	National government	Government	Semi-structured interview
51	Director	National government	Government	Focus group interview
52	Programme Manager	National government	Government	Focus group interview
53	Senior Consultant (Sustainability & Circular Economy)	Consultancy	Business	Focus group interview
54	Consultant (Sustainability & Circular Economy)	Consultancy	Business	Focus group interview

Table 5.1: Overview of interviews

The interviews were conducted in two phases: (1) the author conducted an initial phase of semi-structured interviews with global experts, before (2) conducting on-site semi-structured and focus group interviews, as well as visits to four copper and lithium mining operations in Chile, one of the leading mining countries globally. The reason for choosing this staggered approach was threefold. First, conducting an initial round of interviews enabled the author to establish an initial understanding of CE approaches and thinking in the global mining industry. Secondly, it allowed for an initial interrogation of the conceptual gaps and the iteration of the initial theoretical framework into a draft conceptual framework before conducting in-country fieldwork. Thirdly, it facilitated the identification of a suitable location for an in-depth single case study to *map* the CE approaches used in the mining sector in a specific geographic and regulatory context.

In both phases, interviewees were selected based on a judgement sampling approach (Wolf et al., 2016), where the author created a non-random sample of interviewees based on their knowledge of the topic under investigation. The author's personal connections, industry events, and professional networking sites such as LinkedIn facilitated the selection. To minimise the potential danger of 'group think' arising from reliance on personal and professional networks, efforts were made to include participants from a diverse range of organisations, roles, and geographical regions, ensuring a breadth of perspectives. The author also used snowball sampling methods, where previous interviewees connected them with other interviewees. Interview participants were asked a series of targeted questions to elicit nuanced insights. These questions explored how different stakeholders within the mining define and perceive the CE concept, its alignment with broader governmental and corporate interpretations of CE, and the practical application of CE principles within the industry. Participants were also queried about the mining sector's active engagement with CE approaches, focusing on specific implementation methods, key target areas, and the underlying drivers motivating implementation (see the interview guide in S5. Guide and Sample Questions for Semi-Structured Interviews in the Supplementary Information).

2.2.1. Phase 1 – Initial semi-structured interviews

After completing the initial desk research, the author conducted 14 semi-structured expert interviews with experts from Canada, the United Kingdom, Australia, Brazil, Chile, and South Africa. The interview responses were then used to develop the initial theoretical framework into a draft conceptual framework. Insights from the initial interviews also led to choosing Chile as the location to conduct further intensive fieldwork. Chile was identified by several interviewees as a leader in CE implementation in the mining sector and a progressive policy environment with an interest in transitioning the country's economy towards more circular production and consumption.

2.2.2. Phase 2 – semi-structured and focus group interviews in Chile

For the second research phase, I travelled to Chile, where I conducted 21 individual semi-structured interviews and 5 focus group interviews with 19 participants over 6 weeks. The interviewees were all experts in Chile's mining sector and included policymakers, business leaders, academics, and operational personnel at copper and lithium mine sites. The original interview guide was refined throughout the fieldwork to include questions about emerging themes, such as the impact of specific Chilean policy provisions and unexpected structural waste categories.

2.3. Coding and Data Analysis

After concluding both phases, I transcribed all interview recordings before coding and analysing them, as well as the detailed interview notes with the Nvivo software. I used a primarily deductive yet flexible (i.e. *directed*) coding process (Fletcher, 2017; Hsieh and Shannon, 2005). Initial codes were drawn from the draft conceptual framework and observations captured in a field journal. However, these codes were changed, eliminated, and supplemented with new codes in a way that allowed the initial theory from which they were drawn to be reformulated as new insights emerged (Gilgun, 2011).

The focus of the coding was three-fold: (1) to identify gaps in the conceptualisation of applying CE approaches in the mining sector; (2) to understand the current state of CE implementation in the mining sector; and (3) to capture the CE approaches that the mining industry in Chile uses and the structural waste categories that these strategies target. I began with 25 *provisional* codes - topic-based *bins* into which information was sorted (Maxwell, 2012). These included *bins* for CE understanding, existing CE practices, the type of input and subsequent structural waste that a CE practice was addressing, the resource state of the input a CE practice was addressing, and the value retention option a CE practice was using. These

provisional codes were then altered throughout the coding process, with codes added, changed, or deleted as the data warranted. Throughout the coding process, the 25 *provisional* codes expanded into a total of 58 (see Table 5.2).

Topic	Provisional codes	Final codes
Circular economy understanding	• Value chain perspective • Sub-process perspective • Circular economy principles • Waste hierarchy	• Value chain perspective • Sub-process perspective • Circular economy principles • Waste hierarchy • *Material efficiency* • *Mindset* • *Geographic differences* • *Waste becomes useful* • *Materials-as-a-service* • *Phasing out extraction*

Circular economy practices	• Recycling of end-of-life machine components
	• Reducing the use of machine components
	• Remining
	• Reducing water use
	• Use of byproducts in other industries
		• Recycling of end-of-life machine components
		• Reducing the use of machine components
		• Remining
		• Reducing water use
		  ○ *Desalination*
		  ○ *Purification of wastewater*
		  ○ *Use of seawater in process*
		• Use of byproducts in other industries
		  ○ *Use of tailings in the construction industry*
		• *New business models*
		• *New procurement rules*
		• *Remanufacturing machines and machine parts*
		• *Refurbishing machines and machine parts*
		• *Tyre recycling*

Structural waste categories	• Primary process inputs
	  ○ Rock waste
	  ○ Tailings
	  ○ Slags
	• Secondary process inputs
	  ○ Chemicals
	  ○ Machine parts
	  ○ Organic waste
	  ○ Tyres
	  ○ Water
		• Primary process inputs
		  ○ Rock waste
		  ○ Tailings
		  ○ Slags
		  ○ *Fugitive dust*
		  ○ *Desalination brine*
		• Secondary process inputs
		  ○ Chemicals
		  ○ Machine parts
		  ○ Organic waste
		  ○ Tyres
		  ○ Water
		  ○ *Grinding balls*
		  ○ *Mining machinery*
		  ○ *Oil & lubricants*

Topic	Provisional codes	Final codes
		○ *Plastic* ○ *Steel* ○ *Wood*
Value retention options used	• Short loop • Medium loop • Long loop	• Short loop ○ *R0 – Refuse/Redesign* ○ *R1 – Reduce* ○ *R2 – Reuse* ○ *R3 – Repair* • Medium loop ○ *R4 – Refurbish* ○ *R5 - Remanufacture* ○ *R6 – Repurpose* • Long loop ○ *R7 – Recycle* ○ *R8 – Recovery of energy* ○ *R9 – Remine/Reprocess*
Resource state of structural waste	• Particles • Parts • Products	• Particles • Parts • Products

Table 5.2: Coding Framework

In the next section, the theoretical framing of this work and the conceptual framework that emerged from the desk research and the initial round of semi-structured interviews are described in more detail.

3. Theoretical Framing

The CE can be seen as an *umbrella concept* that aims to offer an alternative to prevalent linear take-make-waste practices by promoting a wide range of waste and resource management strategies with an emphasis on extending the productive life of resources to achieve more sustainable economic outcomes (Blomsma and Brennan, 2017; Pauliuk, 2018). Rather than promoting new strategies for waste and resource management, the CE concept offers a new framing of existing strategies promoted since the 1960s by various scientific fields, such as industrial ecology (Erkman, 1997; Frosch, 1992), industrial symbiosis (Chertow, 2007) and ecological and environmental economics (van den Bergh, 2001). By highlighting the potential of combinations of these existing strategies to extend resource use, the CE concept "constructs

and legitimises a space for the interrogation of the appropriate and effective use of such strategies." (Blomsma, 2018, p.969)

Within this conceptual space, a range of frameworks articulate how a CE might operate by cascading, looping, or cycling resources and waste. (Blomsma and Brennan, 2017). These frameworks, underpinned by their own *logic* (*theory of change*), act as the *frame* through which we understand the problem space and construct high-level courses of action (the *solution space*[8]) (Blomsma, 2018). The most well-known of these frameworks are the Butterfly diagram and the ReSOLVE framework (EMF, 2013, 2012), the Waste Hierarchy (European Commission, 2008), Cradle-to-Cradle™ (Braungart and McDonough, 2009; McDonough and Braungart, 2013), Material Efficiency (Allwood, 2014), but also the Performance Economy (Stahel, 2010) and the Blue Economy (Pauli, 2010).[9] While each framework is underpinned by its own theory of change, overlaps exist: most advocate for reducing virgin material inputs, prioritising reuse and remanufacturing, and closing material loops through recycling or energy recovery. However, they differ in emphasis — for example, the Waste Hierarchy privileges waste prevention and recycling in policy contexts, whereas Cradle-to-Cradle™ promotes regenerative design, and the Performance Economy stresses service-based business models.

Despite these shared principles, the frameworks' differences in scope and *logic* produce varying visions for waste and resource management (Blomsma, 2018; Kirchherr et al., 2023). This diversity has broadened the perceived scope of resource governance and shaped industrial practices (Boons, 2009; Corvellec and Hultman, 2012; Silva et al., 2016).

Yet despite their differences, most CE frameworks claim that they are widely applicable across various scales and that they can be utilised across different stages of the life cycle as

[8] A solution space designates the (set of) solutions that are highlighted as realistic by a problem definition (Dorst and Cross, 2001).

[9] See Blomsma (2018) for an in-depth discussion of each of these frameworks.

well as diverse value chains (Ghisellini et al., 2016; Kalmykova et al., 2018; Kirchherr et al., 2017). However, a critical examination reveals a significant limitation shared by many of these frameworks: they predominantly operate at the macro level and give limited attention to upstream stages of value chains. Dominant CE frameworks often conceptualise raw material production as a material flow outside their scope that should ideally be minimised or eliminated over time.

This limitation is a product of several factors. Firstly, there has historically been a strong emphasis on the waste management of end-of-life (EoL) products in the CE literature (Schöggl et al., 2020). While the broader CE discourse recognises the importance of minimising primary resource use, waste, and emissions, the existing frameworks implicitly focus more on retaining the value of fabricated products and their input materials. Consequently, there has been limited engagement with managing resources within the industrial production processes that are essential for making these products in the first place.

Secondly, the geographical focus of much of the CE research has been on Europe and the Global North more broadly - regions that predominantly consume rather than produce raw materials (Merli et al., 2018). As these regions' economic activities are primarily positioned in the downstream segments of global value chains, CE approaches applied (and studied) in these regions have naturally concentrated on the value chain stages concerned with the production and EoL management of final products (Kalmykova et al., 2018). This focus is further influenced by the fact that these regions have much more rapidly growing stocks of secondary materials than resource-producing regions, which makes downstream CE strategies much more viable and shifts their priorities away from primary resource production (Haas et al., 2023).

As a result, CE implementation is predominantly framed through the lens of value chains that aim to make downstream industrial processes more circular, with less consideration

given to strategies that could make upstream raw material-producing industries—often considered inherently *dirty*—cleaner and more sustainable. This is a significant limitation because it constrains the *solution space* and excludes large segments of the industrial life cycle from mainstream debates on CE implementation. Excluding upstream industries from discussions concerning CE implementation, especially the mining sector, is particularly problematic, as it is the value chain segment that produces the largest amount of structural waste in the entire value chain (Tayebi-Khorami et al., 2019).

There is also a small but, growing evidence base to suggest that implementing CE approaches in mineral resource production systems can help raw material producers operate more sustainably (Golev et al., 2020; Gorman and Dzombak, 2018; Jamett et al., 2022; Lèbre et al., 2017; Upadhayay et al., 2024; Upadhyay et al., 2021). For instance, it has been demonstrated that the management and reuse of tailings, which are often a hazardous by-product of mining, can be improved through the application of CE approaches (Kinnunen et al., 2022; Kinnunen and Kaksonen, 2019; Lebre, 2018). Additionally, using CE approaches to reduce the consumption of water, machinery, tyres, and chemicals within mining operations can significantly reduce resource use and waste, ultimately leading to more sustainable practices (Cisternas et al., 2022).

Therefore, applying CE approaches in industrial systems concerned with producing raw materials represents a largely untapped opportunity to enhance the sustainability of primary mineral extraction operations. However, these industries encounter distinct materials and sustainability challenges compared to downstream industries, which are not adequately captured by existing CE frameworks.

4. Conceptualising Circular Economy Approaches in the Mining Sector

Due to the distinct complexities of the mining sector and other upstream industries, it is crucial to have tools that enable systematic assessments to identify targeted CE approaches that address their specific challenges. I argue that existing CE frameworks lack some contextually appropriate conceptual elements to adequately address the unique complexities of the mining sector and enable the application of CE approaches within the industry. Based on evidence from an extensive literature review and insights from this study's interviews, I have identified three conceptual elements that can help in the design and application of appropriate CE approaches in the mining sector: (1) a clear communication of the *goal and boundary* of the industrial production system that the application of CE approaches is targeting; (2) an identification of the *source and type of inputs* used by the system; and (3) a consideration of the *resource state* of these inputs and the subsequent structural wastes generated from them (Figure 5.2).

The resulting conceptual framework draws on well-established circular economy theories and principles, particularly the 'butterfly diagram' of technical and biological nutrient cycles (Ellen MacArthur Foundation, 2013), the value retention options hierarchy (Reike et al., 2018), and resource-state-based CE approaches (Blomsma and Tennant, 2020). These theories are widely cited and applied across various sectors, providing a robust theoretical foundation that is then adapted for the unique context and requirements of the mining industry. In the remainder of this section, I will explain each of these conceptual elements in turn.

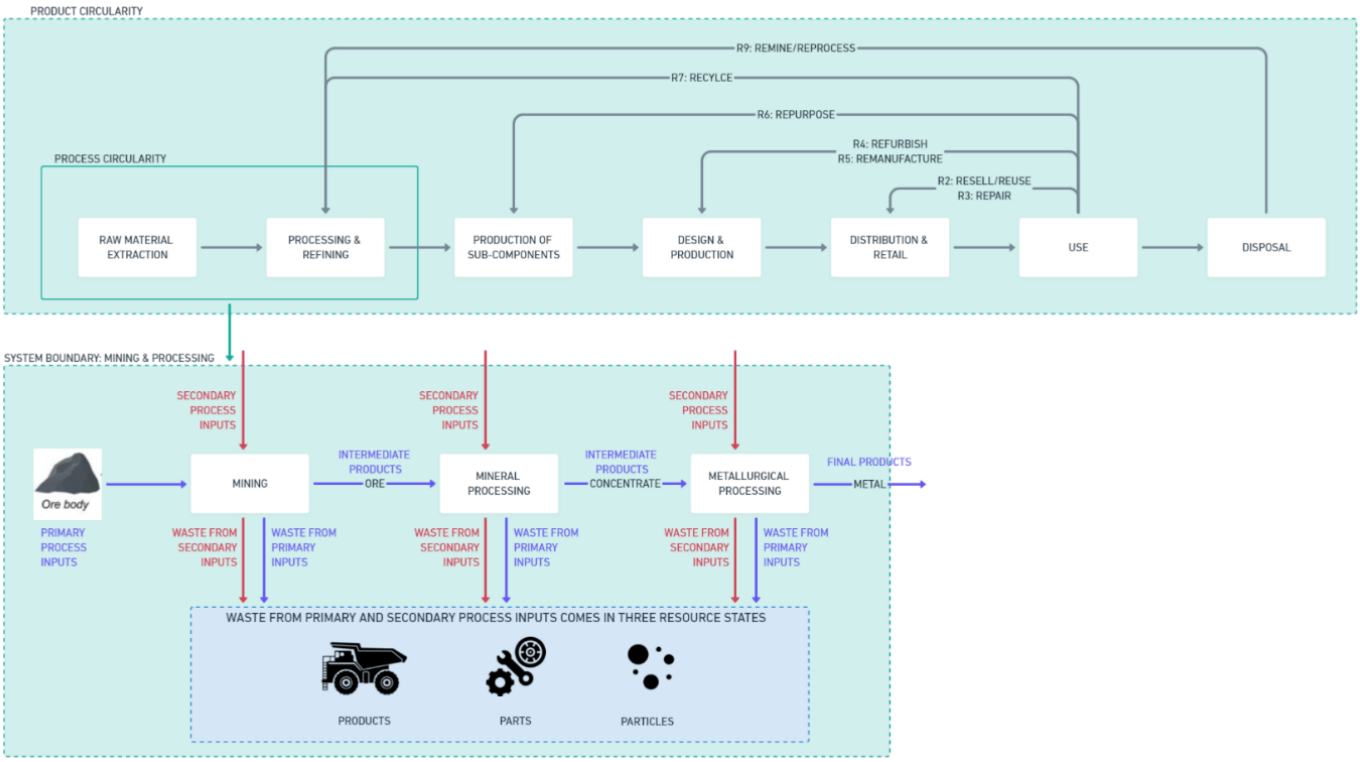


Figure 5.2: Conceptual framework

4.1. Defining the 'boundary' of the system that a CE approaches are targeting

While some CE frameworks acknowledge what aspect of a production and consumption system they try to improve or make *more circular* and what role providers of virgin raw materials should play in a transition towards circularity, a review of the most cited CE frameworks (e.g. the ReSOLVE framework (EMF, 2013, 2012), the Waste Hierarchy (European Commission, 2008), Cradle-to-Cradle™ (Braungart and McDonough, 2009; McDonough and Braungart, 2013), Material Efficiency (Allwood, 2014), the Performance Economy (Stahel, 2010) and the Blue Economy (Pauli, 2010)), reveal that many widely cited frameworks either lack such definitions altogether or apply them inconsistently. Similar concerns about ambiguity in CE frameworks have been raised in the broader literature (e.g. Blomsma and Brennan, 2017; Kirchherr et al., 2023; Korhonen et al., 2018) and have also emerged from the interviews conducted for this study. Responses from the initial 14 interviewees indicated that this presents

challenges for policymakers and practitioners attempting to apply CE thinking and CE approaches in the mining sector. For instance, one interviewee noted that,

> *"currently, the understanding of the circular economy in the mining sector is fuzzy because we have two levels of discussion. One is about the long circle or the value chain. This concerns the urban mine, specifically urban mining and decoupling the extraction of materials with their use. The second approach is to understand CE as closing the loops of sub-processes in different parts of the value chain. For example, retrofitting equipment or trucks or dealing with waste from tyres and tailings. So, for me, today, two groups fight about the concept and the model of circularity in the mining sector. But in my opinion, they are not contradictions. They are instead complementary. But we need to be clear which approach our solutions are targeting."*[10]

Another interviewee echoed these sentiments:

> *"Many will equate circularity with more recycling. Many will equate circularity with waste management. Some will equate circularity with lower consumption. You will hear a lot that circularity is about extending the life of infrastructure and products. Very few will use circularity as a lens to redefine the economy. And it's these multiple perceptions of what the CE is, and what the most powerful CE levers are that don't allow the CE in the mining sector to take off because we are all pushing for different directions".*[11]

Other sustainability frameworks have arguably found a solution to this issue and can be a potential guide to overcoming it. One example is life-cycle assessment (LCA), the systematic analysis of the potential environmental impacts of products or services during their entire life cycle. In LCA, an essential first step when conducting an assessment is to identify its goal, scope and *system boundary*. The *system boundary* defines which processes and stages of a

[10] Interviewee #40
[11] Interviewee #6

product's life cycle are included in the assessment and determines which unit processes, inputs, outputs, and impacts are considered in an LCA (ISO, 2006). It clearly defines what part of a complex system should be analysed and optimised. What became clear throughout the research for this study is that there is currently no equivalent expectation to set a clear system boundary in CE frameworks.

Therefore, I argue that it is essential to introduce an analogue to the system boundary in LCA into frameworks guiding CE strategies. On a high level, it is vital to acknowledge what aspect of the production and consumption system is to be optimised or made 'more circular'. Therefore, as a starting point, CE frameworks could make a more explicit distinction between the use of CE approaches to improve the circularity of a product (*product circularity*) and the use of CE approaches to increase the circularity of one or several industrial (sub-)processes required to produce the ultimate product (*process circularity*). Although both concepts are used in the CE discourse (Pilipenets et al., 2025), the literature review and interviews conducted for this study suggest that their treatment is often implicit or uneven in major frameworks. While *product circularity* takes a value chain perspective and attempts to circulate a specific finished good and/or its components at its highest value, *process circularity* considers how industrial (sub-)processes required to produce these goods and their components can become 'more circular' by eliminating waste and pollution, improving material and resource efficiency in the production process.

This has several advantages. First, by adopting a clear distinction between product and process circularity, and establishing precise system boundaries for CE approaches, frameworks can be significantly more relevant and effective for upstream industries. For example, within the mining sector, this refined approach allows for targeted approaches that address the EoL management of products and the intermediate processes that generate substantial structural waste. Secondly, this distinction enhances the applicability of CE principles by recognising that

upstream industries often operate under different constraints and opportunities compared to production systems further down the value chain. By focusing on the impacts and efficiencies of specific industrial processes, rather than solely on their final products, CE strategies can foster more sustainable practices within these industries' control. This paradigm shift is essential for integrating CE into the core operations of upstream industries, enabling them to contribute more effectively to the overall goal of transitioning to a CE.

4.2. Identifying the source and type of structural wastes generated by an industrial production system

Once a clear system boundary has been defined, developing a systematic understanding of the industrial processes targeted for improvement and the inputs these processes use is imperative. Every industrial production system is, at its core, a transformation process that takes one or more inputs, transforms and adds value to them and provides outputs to customers and clients, known as products. However, this transformation process is significantly less efficient in upstream industries than in downstream industries, as raw materials contain more significant amounts of impurities than more homogeneous and refined inputs in later value chain segments (Kalisz et al., 2022). Thus, manufacturing processes tend to be more efficient than raw material extraction processes and convert a higher percentage of input material into the final product, generating less structural waste.

As a result, in many upstream processes, such as mining, the final products that emerge from these production systems are often dwarfed by the vast quantities of resource inputs that ultimately become structural waste. As one interviewee observed, "*Mining is a largely extractive business with classifications for most things to be considered as waste. Mining companies typically have one high-value by-product being the commodity they sell, when really, the majority of their business is managing all of the other resource inputs that it takes*

to make that high-value byproduct".[12] This insight underscores the importance of comprehending the full scope of the materials being used, transformed or produced within an industrial production system.

The core goal of CE strategies is the replacement of the current linear 'take-make-use-dispose' system with a system that addresses these sources of structural waste (EMF, 2013). However, what constitutes the most important type of waste is highly context-dependent (Blomsma and Tennant, 2020). Hence, I argue that it is crucial to understand both the sources and types of structural waste and inputs in a production system to formulate effective CE strategies.

On a high level, structural wastes can come from two sources: (1) *primary input materials* that are transformed into a higher-value product, such as metal-bearing ores in the case of mining; or (2) *secondary input materials* that enable the transformation process, such as machinery, processing chemicals and labourers. Making this distinction matters for several reasons. On the one hand, upstream companies have different levels of control over using each type of input and the subsequent structural waste generated from them. While *secondary inputs* are primarily provided by third-party actors (suppliers) whose production process is difficult to control by the upstream firm, *primary inputs* are extracted and processed by the upstream firm itself, giving it control over how this process is designed and conducted. This matters as a firm's level of control over its inputs is directly linked to its ability to influence the use of CE strategies, with firms with higher levels of control over their supply chain displaying higher levels of applying CE approaches (Elia et al., 2020).

On the other hand, the volume of waste generated from the two input sources differs significantly. The quantity of waste generated from *primary inputs* often far outstrips the

[12] Interviewee #5

structural waste generated from *secondary inputs*. Depending on the industrial process, the structural waste from primary inputs generated in the production system can even be significantly larger than the product(s) of the industrial production process itself. For example, in the copper mining industry, the average rock-to-metal ratio[13] is 1:510 (Nassar et al., 2022). This means that for every tonne of copper shipped to a customer, a copper mining operation will have generated 510 tonnes of structural waste from its primary inputs to generate its product.

4.3. Resource state of the structural wastes that are generated by an industrial production system

The CE literature has emphasised the importance of distinguishing between *products* (i.e. finished goods), *parts* (i.e. components of finished goods) and *particles* (i.e. elements, substances, molecules or materials) when it comes to the development of CE approaches (e.g. Blomsma and Tennant, 2020).

However, these so-called *resource state* frameworks have been predominantly applied from a value chain perspective with different *resource states* associated with different value chain segments, such as the particle state with the extraction of raw materials through mining or agricultural production and the product state with the use phase of products. However, in our interviews, the majority of mining firms reported that they handle structural wastes across all three resource states, challenging the conventional assumption that upstream operations are primarily concerned with *particles*. This indicates that each resource state cannot be neatly associated with a single segment of the value chain. On the contrary, upstream firms must manage inputs and structural wastes in the product, part, and particle states simultaneously.

[13] The quantity of ore mined and waste rock (i.e., overburden or barren rock) removed to produce a refined unit of a mineral commodity.

This is a highly important nuance, as the *resource state* of structural waste generated by an industrial production system influences the CE approac that can be implemented. By conserving resources and reintegrating final products and structural waste into processes, CE practices offer a comprehensive approach that spans the design stages to behavioural changes in material reduction and reuse (Kalmykova et al., 2018). They can be categorised into three circularity loops: short, medium, and long. The primary difference between the loops is the proximity of the products to the users and their final function. Longer loops result in less efficient systems, making them a less desirable form of circularity. Each loop provides various alternatives to maximise the value of by-products and waste, incorporating them into the same or different industrial production processes. Each alternative can be referred to as a value retention option (RO) (e.g. recycle, reuse, reduce) (Reike et al., 2018).

Traditionally it was only rarely acknowledged that not all ROs are feasible or desirable to implement in all circumstances. However, more recent evidence has shown that the feasibility and desirability of specific ROs depend on a firm's existing supply chain position and business model (e.g. Cisternas et al., 2022; Reike et al., 2018). I contend that in addition to these factors, the *resource state* of a structural waste category also constrains the ROs that can be deployed (see Table 5.3). In particular, while all ROs are available for structural waste streams in the *product state*, several short and medium loop ROs do not apply to the waste streams in the *part and particle states*. Thus, it is crucial to understand the *resource state* of production systems' inputs and structural wastes, as this will determine the available options for designing CE strategies.

Loop	Emphasis	Value retention option	Description	Particle	Part	Product
Short	The material remains close to the user and end-use	R0: Refuse/Redesign	Avoid the use of materials	✓	✓	✓
		R1: Reduce	Use less material per unit of product	✓	✓	✓
		R2: Reuse	Use existing materials for a different purpose	✓	✓	✓
		R3: Repair	Extend the life of a material	✗	✓	✓
Medium	Parts or products are updated rather than discarded	R4: Refurbish	Replacement or repair of a part of a multi-component product that results in a general update	✗	✓	✓
		R5: Remanufacture	Reconditioning of the complete structure of a multi-component product	✗	✗	✓
		R6: Repurpose	Use discarded materials for a different function than the original	✓	✓	✓
Large	Traditional waste management. Products lose their original function	R7: Recycle	Treating discarded materials using a special industrial process so that they can be used again	✓	✓	✓
		R8: Recovery of energy	Capture energy contained in waste and integrate it into other processes	✓	✓	✓
		R9: Remine/Reprocess	Recovery of materials after final disposal	✓	✓	✓

Table 5.3: ROs in the mining industry. Adapted from Cisternas et al. (2022) and Reike et al. (2018)

Next, I explain how these new conceptual elements can help map the application of CE approaches in the mining sector and identify gaps in the sector's current approach to circularity.

5. Analysis & Results – Application of CE Approaches in Chile's Mining Sector

Chile is the world's largest producer of copper and the second-largest producer of lithium. Discussions about the CE have been growing in Chile in recent years, as evidenced by the development and publication of the *Roadmap for a Circular Chile by 2040* in 2021 (Ministerio del Medio Ambiente, 2021). One of the key policy tools to drive this strategic ambition is the Extended Producer Responsibility (REP) law enacted in 2016 (Government of Chile, 2016). By attributing the responsibility for waste management directly to the producers of specific categories of products, the REP law seeks to instigate a paradigm shift towards more sustainable waste management and recycling practices across various sectors. The law focuses on "priority products" such as packaging, batteries, tyres and electrical appliances, and compliance is structured in stages to facilitate gradual adaptation and effective implementation.

Although mining is the largest economic sector in Chile, it was initially not a key focus of the policy shift toward the CE paradigm and its associated legislative changes. However, recent years have seen an increasing interest by both policymakers and industry decision-makers to see the mining sector apply CE approaches. For instance, the Ministry of Mines is increasingly involved in CE policy discussions among government bodies. This is exemplified by the integration of CE concepts within the National Mining Policy (Ministerio de Mineria, 2022) and the publication of *Circular Economy Indicators in Chilean Mining* by the Chilean Copper Commission (2023), which has forced the industry to engage more actively in discussions about how a CE transition can be achieved. In 2019, the state-owned *Production Development Corporation of Chile* (CORFO) funded the first circular economy centre in South America, the *Circular Economy Technology Center for the Northern Macrozone* (CircularTec).

CircularTec is due to receive US$ 21.5 million by 2030 to promote CE practices in four of Chile's Northern regions and has a strong focus on applying CE approaches in the mining sector. In addition, many mining companies active in Chile have launched overarching CE strategy documents, detailing their ambitions to use more circular approaches in their operations and contribute to the transition towards a CE. However, none of these strategies explicitly distinguishes between product and process circularity approaches.

5.1. System boundaries of CE strategies in Chile's mining sector

Despite having the OECD's fourth-lowest GDP per capita, Chile has the bloc's second-highest domestic material consumption rate and its lowest total material productivity (OECD, 2024). It means that Chile produces significantly more structural waste per capita than much richer countries. This is driven by the immense quantity of structural waste produced by Chile's mining sector. Although recent data is scarce about the impact of mining on Chile's overall resource use, as early as 2000, over 90% of resource use in Chile, was structural waste from the copper mining industry (Giljum, 2004). Despite these stark numbers, Chile's CE policy roadmap does not once mention the mining industry and thus does not address this largest source of structural waste generation. As a result, there is currently a lack of clear goals when it comes to the application of CE approaches in the mining sector in Chile.

Instead, Chile's CE policy landscape has predominantly promoted a product circularity approach - primarily through the *REP law* and the *Roadmap for a Circular Chile by 2040*. These policies aim to address end-of-life (EoL) waste management of products consumed within Chile, aligning with broader global discourse observed in regions like the EU and China (McDowall et al., 2017; Ogunmakinde, 2019). This approach emphasises the recycling and reprocessing of products post-consumption to extend their lifecycle and reduce waste. As a result, current policies and regulations targeted at promoting the CE, are only impacting Chile's

mining sector when it comes to managing EoL products used in the production process that fall under the REP law. A Chilean government official confirmed this view,

> *"the Ministry of Environment is the lead of Circular Economy policies. They have a circular economy office. And they are in charge of implementing and updating the REP law. They prioritise seven kinds of waste, like tyres and batteries and packaging among others. And some of them are related to the mining industry, such as tyres, big tyres of the of the big trucks that we use in copper mining. I think that is the key effort from the state."*[14]

Although mining companies are some of the most significant users of some of the product categories covered by the REP law, these waste streams only make up a very small proportion of the total volume of structural waste produced by the sector, as the following sections will show. In addition, mining companies have limited influence over the design and supply chain of third-party-supplied products. Hence, a *product circularity* approach has limited relevance for mining companies.

Findings from the interviews with industry stakeholders support this. In particular, out of 154 mentions of the most impactful CE approaches the mining industry could adopt, only 2% pertained to a *product circularity* approach, such as expanding business activities to include downstream recycling of end products or developing innovative business models like leasing metals instead of selling them. Conversely, the majority of impactful CE approaches are focused on optimising resource and material efficiencies and reducing the environmental footprint of mining production processes, which can all be defined as *process circularity*.

[14] Interviewee #18

5.2. Identifying the source and type of structural wastes generated by Chile's mining production system

The focus of these CE strategies and practices focused on process circularity can be broadly divided into two categories: (1) re-thinking the consumption patterns and the end-of-life waste management of secondary inputs used by mining companies (*secondary process inputs*); and (2) managing the structural waste that is generated in the process of extracting and beneficiating mineral-bearing ores (*primary process inputs*). Each stage of the mining process produces large amounts of both (see Figure 5.3).

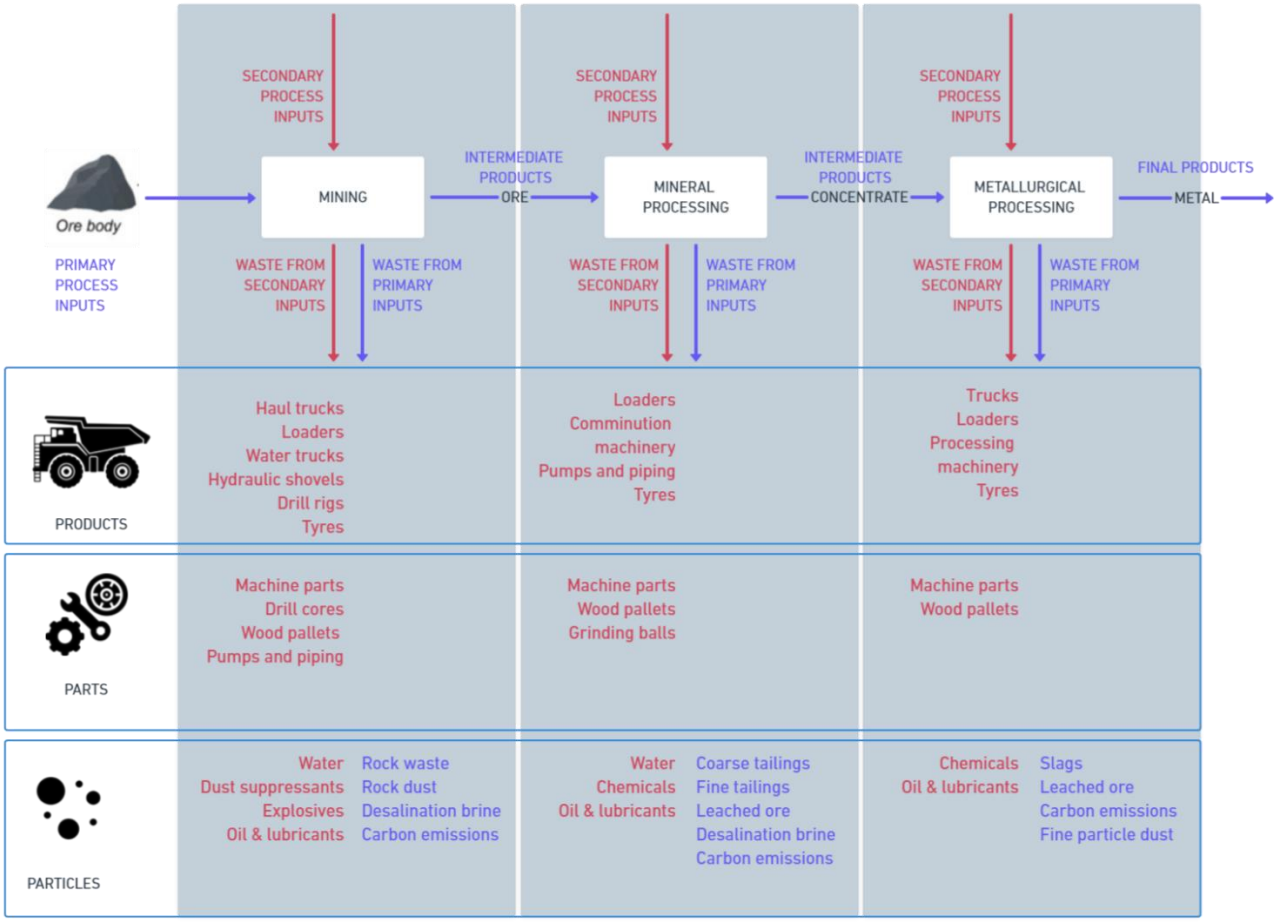


Figure 5.3: Selected structural wastes in the copper production process

The interview results indicate that CE approaches in the Chilean mining sector are discussed in relation to managing structural waste from both *primary and secondary process inputs*. Specifically, 55% of interviewees mentioned the management of structural waste and

resource use from *secondary process inputs*, while 45% referred to managing *primary process inputs*. While these proportions suggest a relatively similar level of attention in the discourse, they do not necessarily reflect the extent to which this is implemented in practice.

5.2.1. Primary Process Inputs

Mining produces a significant amount of structural waste in the process of extracting and beneficiating mineral-bearing ores. Mining is considered to be the largest waste producer by quantity globally, with an estimated worldwide generation of solid wastes from the primary production of mineral and metal commodities of over 100 billion tonnes per year, including tailings, rock waste and smelter slags (Tayebi-Khorami et al., 2019). Moreover, especially in dry countries like Chile, open-pit mining can cause localised air pollution due to the fugitive dust emitted in the process of blasting and hauling ores (see Figure 5.4).

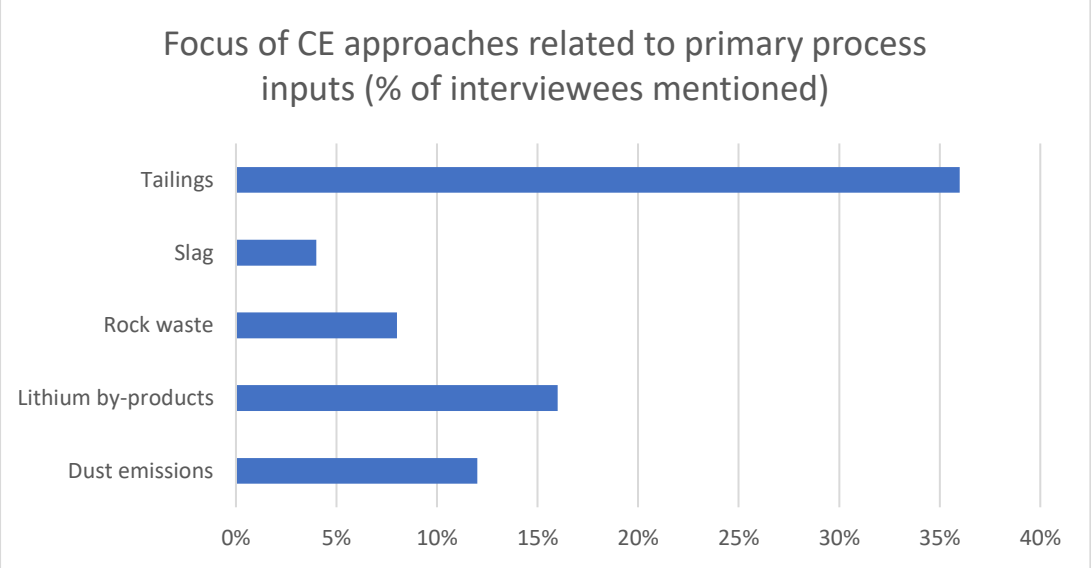


Figure 5.4: Primary process inputs

In Chile, tailings, the waste materials left after the target mineral is extracted from ore, emerged as the key focus area. Over 35% of interviewees discussed existing or planned CE projects to tackle tailings. Tailings are a particularly pressing issue in Chile, where large-scale

mining operations have been ongoing for over a century. As a result, Chile has 764 tailings deposits, of which 110 are active, 473 are inactive, 173 are abandoned, and 8 are in the construction stage (SERNAGEOMIN, 2024). It is estimated that more than 26.3 billion tonnes of tailings are stored in tailings deposits across the country, the third most of any country (COCHILCO, 2022). In addition to the historic burden, operating copper mines are estimated to generate nearly 600 million additional tonnes of tailings each year, a number projected to increase to 1 billion tonnes or more in the next decade due to falling ore grades and a rise in ore volumes processed (COCHILCO, 2022). Over 90% of interviewees highlighted tailings as the most fundamental risk for the mining industry in Chile. Storing such large volumes of tailings not only necessitates using large land areas to accommodate mining operations and traps a significant volume of process water that is not available for recycling, but over the years, there have also been several incidents of dam failures and disastrous releases of tailings (Wang et al., 2014).

Interviewees emphasised various strategies to manage tailings, such as remining and reprocessing, to recover valuable materials and reduce environmental impact. As one respondent, a senior researcher at a think tank, described:

> *"I think with the tailings in the circular economy, you could talk for hours about it, because I think there's an initial focus on mineral recovery, but when it comes to minerals or valuable minerals in tailings we're talking, you know, 0.2%, or something. You're not going to make a huge difference to the tailings volumes by recovering the valuable minerals. But there's also been interest in construction materials from using the basic tailings material. And now I think there's a bit of a shift upstream to looking at processing, pre-concentration of mineral of the ore, to take away a lot of the material prior to concentration, because that obviously gives a lot of benefits around lower energy use, lower water use, lower transportation costs, lower tailings volume, all by*

taking away the waste upstream, which can then be repurposed, potentially, for construction materials as well."[15]

5.2.2. Secondary process inputs

Chile's mining industry also consumes large amounts of resources through *secondary process input,* including industrial mining machinery, machine parts, process water, chemicals, and oil and lubricants. These become waste at the end of their useful lives. Interviewees discussed various existing and possible CE strategies and practices to manage the consumption and EoL management of various *secondary process inputs*. Despite the wide range of secondary process inputs associated with CE interventions by interviewees, water and tyres were by far the most frequently mentioned (see Figure 5.5).

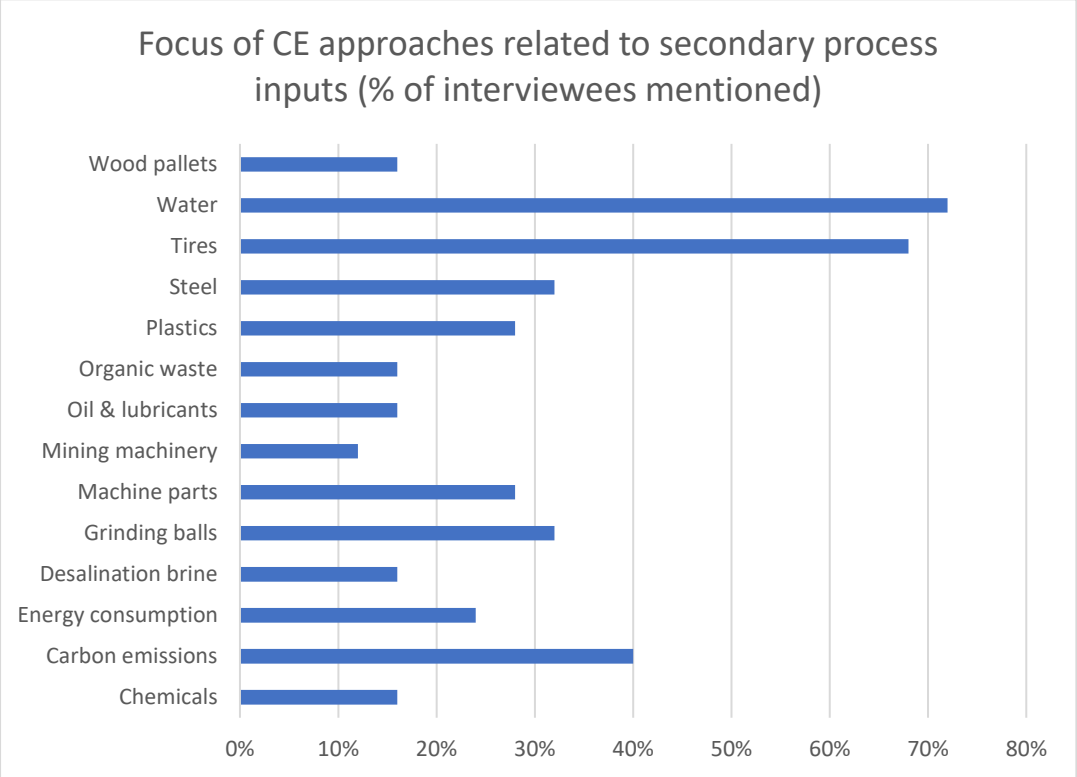


Figure 5.5: Secondary process inputs

[15] Interviewee #44

In Chile, water use is of particular focus due to the arid conditions in its Northern regions, where mining operations are most intensive. This already challenging situation has been exacerbated by a devastating drought that has been ongoing for more than 15 years. Hence, efficient water use to mitigate the significant impact on local water resources is a critical focus for the mining industry. As a result, mining companies are increasingly trying to change their processing technologies to use less water while also increasing the use of desalinated water to reduce the reliance on scarce continental freshwater resources. However, the desalination process to transform salt water into clean water used in the copper ore beneficiation process produces large amounts of salty brines that are disposed of in the ocean. The mining process also generates large amounts of GHG emissions, particularly through fossil-fuel-based propulsion of mining machinery.

Tyres are also a primary focus due to their extensive use in mining operations and the resulting significant amount of structural waste generated when they reach the end of their useful lives. It is estimated that an average large-scale mine in Chile uses around 3,000 tonnes of tyres annually (Weibold, 2022). For example, Escondida, the world's largest copper mine uses over 160 haul trucks, each requiring six tyres weighing over 5 tonnes each. The REP law has been a driving force behind efforts to manage end-of-life (EoL) tyres. This legislation requires the mining industry to recycle 25% of its EoL tyres and store at least 50% either directly or through third parties, with a goal to fully recycle or reuse all tyres by 2030 (Moore, 2023). As one interviewee remarked: *"The regulation did seem to have kicked off some of that thinking in industry, like the Extended Producer Responsibility Act. At least on the tyres, on the kind of small c circularity"*[16].

[16] Interviewee #44

Despite this regulatory push and the widespread awareness of EoL tyres as a focus area of CE implementation, only 5% of CE projects identified by interviewees were specifically aimed at tackling EoL tyre waste (see Figure 5.6). This discrepancy highlights the challenges in bridging the gap between policy aspirations and practical implementation.

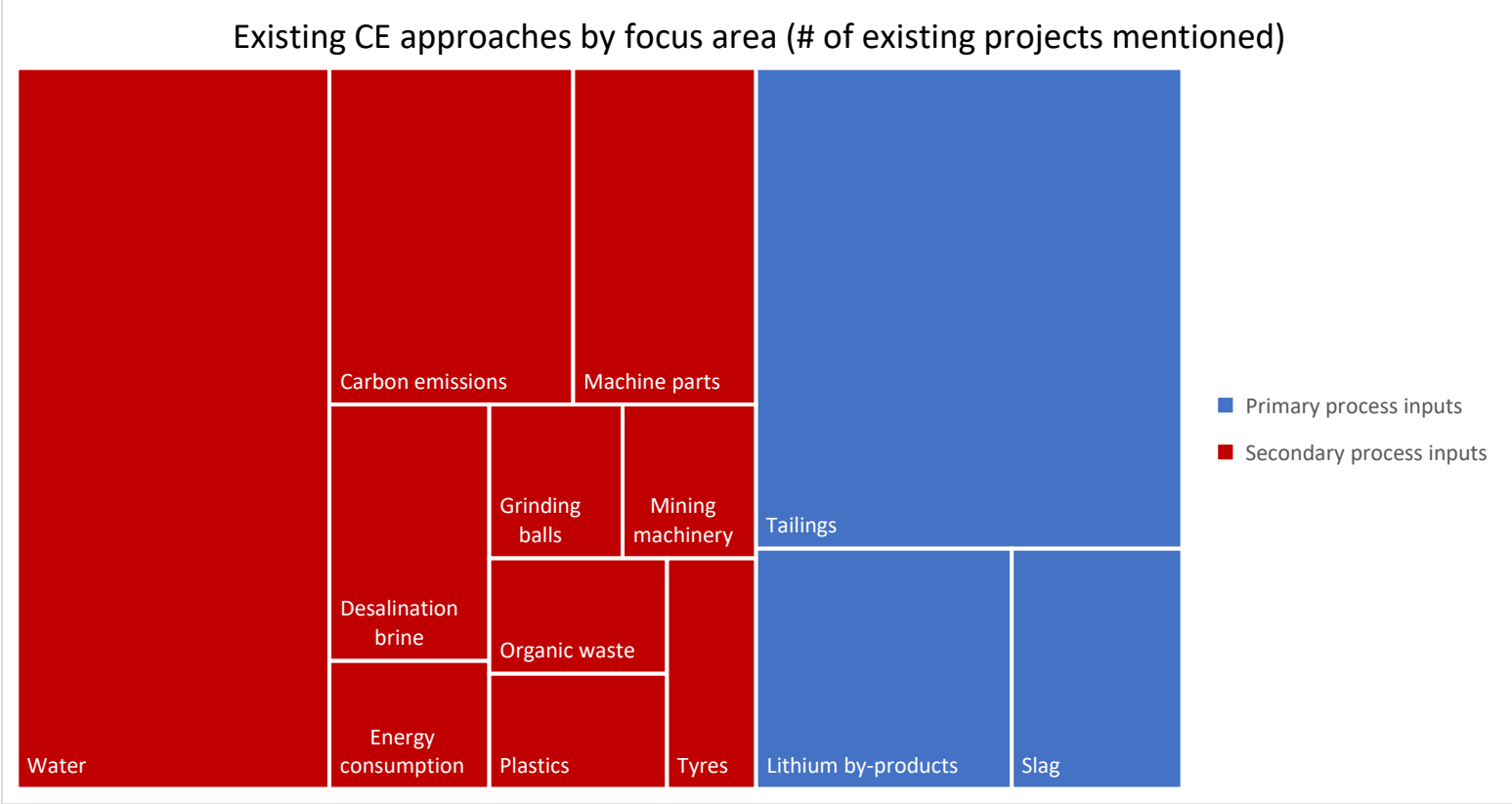


Figure 5.6: Existing approaches by focus area

5.3. Resource states of the structural wastes generated by Chile's mining sector

Despite the relatively even distribution of focus on primary and secondary process inputs, the picture is more complex regarding the *resource state* of the materials and waste streams within each category. The focus distribution between different *resource states* varies significantly between primary and secondary process inputs. For primary process inputs, the emphasis is predominantly on materials and waste streams in a particle state, which is characteristic of mining activities where most waste occurs in this form. This includes tailings, slags, and other

particulate waste materials (see Figure 5.7). Tailings are a prime example of waste in the particle state. Similarly, slags, another common particle waste in metal processing, can be repurposed for use in construction and road building.

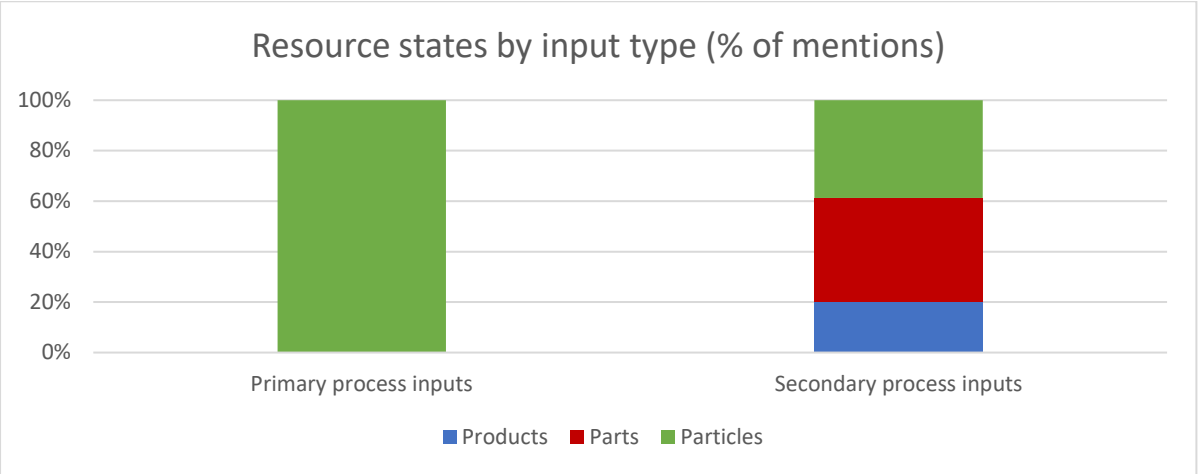


Figure 5.7: Resource states

In contrast, secondary process inputs display a more balanced distribution between part and particle states. Parts account for 41% of mentions, while particles account for 39%. This balance indicates a comprehensive approach to managing solid and fragmented materials, encompassing various inputs from machinery parts to consumable materials. For instance, machine parts and grinding balls are critical inputs in copper mining operations, and their reuse or recycling can significantly reduce material consumption and waste generation. The balance between parts and particle states in process inputs also reflects the diverse nature of the materials and resources used in mining. While some materials, like water and chemicals, are consumed in large quantities and require efficient management to reduce waste, others, like machinery parts, can be refurbished or remanufactured to extend their lifecycle and reduce the need for new inputs.

Interestingly, despite the REP law targeting mostly waste streams in a product state, there is limited focus on this *resource state* by mining companies. This limited attention can be attributed to several factors. Firstly, the quantity of structural waste streams in a product state

is significantly lower than other waste streams. Consequently, mining companies may not see the economic or environmental benefit of focusing on these lesser quantities. Additionally, in line with EPR principles, the management of such waste streams is often viewed as the responsibility of suppliers. This perspective stems from the outsourcing culture prevalent in the mining industry. Suppliers are expected to recover, repurpose, or responsibly dispose of materials.

However, the findings indicate that while suppliers may have both the willingness and technical capacity to manage these streams more circularly, they are often constrained by the administrative controls and contractual frameworks imposed by mining companies. Several interviewed suppliers highlighted the bureaucratic challenges and mining industry mindset that prevent them from implementing innovative CE practices. For example, one supplier explained:

> *"Their [the mining companies'] paperwork is really making things hard. […] Because right now, sometimes they have 50 tonnes of metal from a broken piece of equipment. I cannot say to the mining company: 'Leave it here, sell it to me, and I can make new products.' No, they keep it and sell it as low-value scrap, which increases carbon footprint, it increases costs and stops circularity."*[17]

This suggests that, although EPR principles position suppliers as the primary actors for such waste streams, current industry structures may require greater collaboration and flexibility from mining companies to enable suppliers to implement CE approaches.

5.3.1. Value retention options (ROs)

Finally, interviewees reported the use of a diverse range of ROs across all three circularity loops (short, medium, and long) to tackle these focus areas. However, there is a marked focus

[17] Interviewee #15

on short and long-loop ROs, with less attention paid to medium-loop strategies, such as refurbishing (R4) and repurposing (R6). The most frequently mentioned strategies include: Reduce (R1), recycle (R7) and remine/reprocess (R9). These three ROs collectively account for over 68% of mentions, indicating their central role in the CE strategies of mining companies active in Chile (see Figure 5.8)

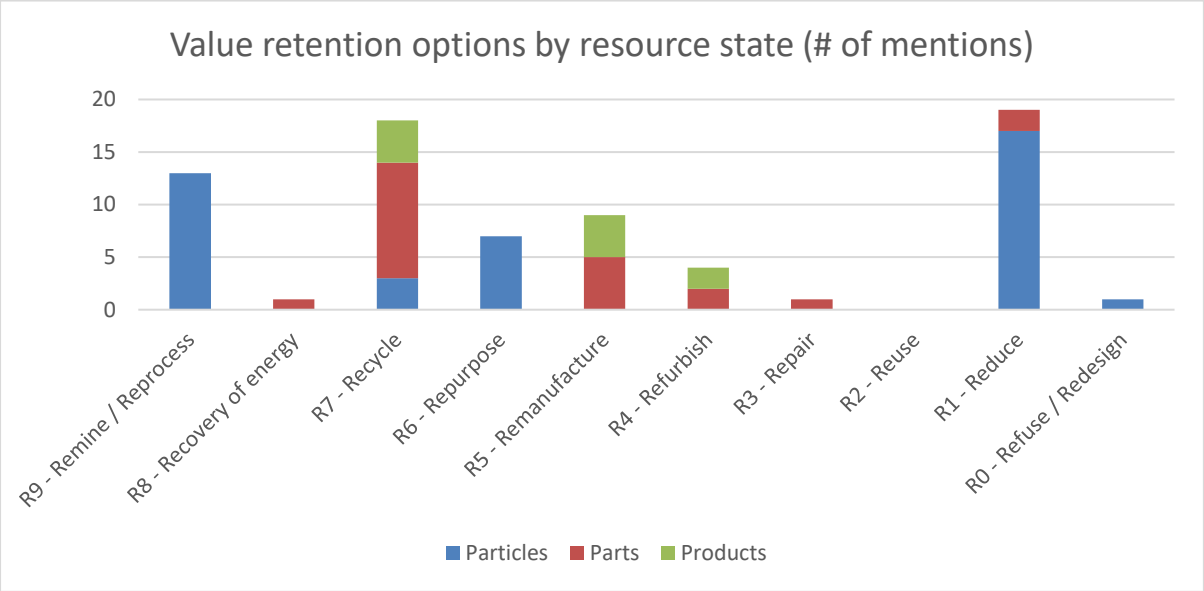


Figure 5.8: Value retention options by resource states

However, the ROs used vary significantly between the three resource states. For the particles state, the emphasis is on remining and reprocessing (R9) to recover valuable materials from waste streams and reduce material use (R1). Tailings, slags, and other waste products are targeted for either reprocessing to extract residual metals and minerals that can be reintroduced into the production cycle from existing waste stockpiles, such as tailings dams, or reduction of the production of these structural wastes in the first place to alleviate the pressure to expand existing waste storage facilities. In contrast, the industry's focus for wastes in the parts and products states is predominantly on recycling materials used in mining operations. Recycling (R7) and some medium loop strategies, such as remanufacturing (R5) and refurbishing (R4), are commonly applied to reduce the structural waste from machinery that has reached its EOL. For example, one of the larger local

manufacturers of water pumps in Northern Chile has launched an ambitious offering to refurbish and remanufacture pumps for mining clients. At the same time, a large-scale copper mine recently introduced new procurement rules that give an edge to suppliers that can offer product life extension or EOL recycling services.

6. Discussion

The mapping exercise of CE approaches within Chile's mining sector, conducted using the three conceptual elements of resource state, source of process input, and structural waste type, highlights three recurring themes that emerged directly from the coded interview data and document analysis. These insights can be categorised into three key themes: (A) the inherent complexity of CE transitions in the mining sector, (B) the limited systemic thinking in current CE approaches, and (C) the rebranding of existing sustainability efforts as CE practices. Each theme connects to specific empirical findings presented in Section 5, and together they have significant implications for the application of CE approaches in the mining sector.

6.1. Complexity of CE transitions in the mining sector

The first major theme of this study’s findings is the inherent complexity of CE transitions in the mining sector. Based on the observations presented by the interviewees in Section 5.1, it becomes clear that, unlike downstream industries, which often deal primarily with structural waste in a product state, upstream sectors like mining contend with materials and waste streams across all three resource states: particles, parts, and products. This diversity complicates the development and application of CE approaches. In mining, the particle state dominates (e.g., rock waste, tailings, slag), but parts (e.g., machinery components) and products (e.g., tyres, water pumps) are also significant.

This complexity necessitates a multi-faceted approach to CE, addressing various types of structural wastes across different resource states. Although this complexity increases the difficulty of successfully applying CE approaches, evidence suggests that successful CE implementation requires adopting multiple CE approaches across different resource states within *circular configurations*, rather than improving isolated processes (Blomsma and Tennant, 2020). These *circular configurations* involve synergies and trade-offs between various CE approaches, necessitating a comprehensive understanding of how these strategies interact and function together (Blomsma et al., 2023). This suggests that mining companies should apply CE approaches in an integrated manner, where synergies between different CE approaches are actively sought and managed in ways not previously practised in linear economic models if they want to deliver real change by adopting CE practices. For example, a mining operation could pair the integration of a closed-loop water recycling system for ore processing (particle state), with a remanufacturing programme for water pumps and pipes (product state). Together, these measures would reduce both freshwater withdrawals and the demand for new components. Such integration contrasts with the current pattern of implementing isolated efficiency projects, where water reuse and equipment procurement are planned and budgeted independently.

6.2. Limited Systems Thinking

However, the development and execution of such circular configurations require an understanding of how CE approaches function as a set across flows of materials, energy, information and value together (Blomsma et al., 2023). Yet, mining firms currently only implement individual measures to address specific sustainability challenges without altering their core business models or mining processes. This second theme reflects findings in Section 5.2, where interviewees described CE approaches implemented in isolation rather than as part of a coordinated set. This leads to a situation where mining companies implement CE practices

that align with their current operations and regulatory requirements, rather than investing in innovation activities to find new solutions that could fundamentally improve their business model or the industrial processes used to extract minerals.

This piecemeal approach creates a bias for incremental improvements to enhance the efficiency and sustainability performance of existing production systems, rather than allowing for a fundamental rethink and redesign of the extractive production system through changes to business models, mining methods, or industrial processes. For instance, while some companies have reduced their water usage and are slowly establishing new supply chains for recycling haulage truck tyres, these efforts are isolated and do not constitute the systems thinking required for scaling up CE approaches beyond small projects.

This behaviour reflects a broader trend within the industry to opt for incremental improvements aimed at cost reduction rather than systemic changes, driven by the high upfront costs, long life cycles, and operational complexities associated with mining (Daly et al., 2022; de la Torre de Palacios and Espí Rodríguez, 2022). Limited innovation in mining is often attributed to these long path dependencies and significant upfront costs (Bartos, 2007; Calzada Olvera and Iizuka, 2024). However, the inherent complexity of the mining process and the need for significant upfront investments make it even more important to design out waste and focus on material efficiencies from the outset. This insight aligns with eco-design theory, which emphasises the critical role of the design stage in achieving higher levels of circularity (Ryn and Cowan, 2013).

6.3. Rebranding and Additionality of CE

The third theme, grounded in the findings from Section 5.3, is the rebranding of longstanding sustainability initiatives under the CE label. Several interviewees explained that mining companies want to be perceived as leaders in implementing CE approaches despite limited

investment in innovation. As a result, several existing workstreams on critical sustainability challenges are now being *rebranded* by mining companies and their suppliers as efforts to make the industry "greener". For example, water management, long a critical sustainability challenge for Chilean mining companies, is now frequently rebranded as a strategy to make mining operations "more circular."

Similarly, in light of the environmental disasters caused by the recent accidents at the Mariana and Brumadinho tailings dams in Brazil, there has been significant pressure from international financial investors to lower the environmental risks associated with storing structural waste from primary process inputs. As a result, companies increasingly describe longstanding efforts to manage the large amounts of copper tailings accumulated over decades as an example of adopting CE practices. Other long-running environmental initiatives, such as minimising structural waste from secondary process inputs used in mining operations through practices from composting, zero waste to landfill projects, to finding new uses for large quantities of plastics, wood pallets and grinding balls, are also increasingly rebranded as CE practices.

While this rebranding trend can be seen as a positive step in raising awareness and aligning with contemporary sustainability paradigms, it also raises questions about the additionality CE approaches. Specifically, whether CE implementation genuinely drives new ways of working or simply repackage existing activities under a new label. As one former senior mining executive who is now an industry consultant and executive of an industry association explained:

> *"I am about to start a project in which I need to make some kind of a forecast of the potential demand for circular technology for mining. And it sounds very fantastic. But what is that? So when we started talking to different players in the industry, you come back to the usual things: tailings dams, grinding balls, recirculation of water. Okay, in*

what way in which you're approaching that problem is it different? And really, it's not. Yes, they will say that the standard is higher, you need to move stronger in order to reduce the consumption of water or to make it circular and recycle water completely. Okay, but that's what we have been doing over the last 50 years. So, therefore defining what are the demands for circular technology in order to make a transition, let's say from the traditional mining industry to a mining industry that is embedding the complete paradigm of circular economy? How to make that assessment?"[18]

This highlights a potential risk to the CE paradigm, where the term becomes more about marketing and less about substantive change. While this can initially drive engagement and visibility, it is crucial to ensure that the implementation of CE approaches leads to real, measurable improvements in sustainability and is not just a rhetorical shift – a trend that has also been witnessed in other industries (Kopnina, 2019)

6.4 Lessons/Implications

This study's results have shown that the mining sector encounters distinct material and sustainability challenges compared to downstream industries. Thus, it becomes clear that considering a CE transition as a uniform process across every industry is counterproductive and that systematic assessments are essential to uncover targeted approaches that address each industry's unique challenges. To this end, the systematic mapping exercise conducted in this study is the first step to establishing such a systematic assessment. This begins with developing an understanding of the specific input materials used in each industrial process and the subsequent structural waste it generates. Conceptualising and mapping the types of materials and structural waste produced by an extractive process helps identify hotspot areas where CE approaches might be used to improve said process. This approach involves questioning the

[18] Interviewee #26

choice of industrial processes currently deployed in a mining operation vis-à-vis its alternatives, as this choice ultimately determines the industrial system's environmental impacts and material efficiency.

Finally, it becomes clear that if the mining sector is to fully leverage the potential of the CE paradigm, it must move beyond incremental improvements and rebranding to genuinely integrate CE thinking and approaches into its core operations. This would involve adopting a more holistic and integrated approach to implementing CE approaches that address structural waste from different types of process inputs in various resource states in a coordinated manner. In addition, to apply CE approaches effectively within the mining sector, it is crucial to adopt a system boundary that focuses on the circularity of industrial processes rather than products. While governments should encourage both product and process circularity, process circularity is especially important in mining, where environmental impacts are concentrated in extraction and processing, rather than in downstream product use. Focusing on process circularity allows policy and practice to directly minimise waste and optimise resource efficiency within industrial operations themselves.

7. Conclusion

This paper has examined the application of CE approaches in the mining sector. While much of the existing CE discourse is centred on downstream activities, such as recycling and product reuse, this study has explored how CE principles can be applied to upstream activities, which remain comparatively underexamined in the literature. In light of the growing understanding of the need for continued primary material extraction, this paper aims to broaden our knowledge of how CE approaches can be operationalised across different stages of production systems, including primary material extraction.

To support this exploration, the study applied three conceptual elements to map CE approaches in the Chilean mining sector systematically. Although these three elements have previously been used within CE research, their integrated application to an upstream, extractive context provides a structured way to identify opportunities for circularity within mining operations. In particular, by focusing on the source and nature of the material inputs and structural waste outputs used and generated by extraction processes, the resulting conceptual framework allows for a more targeted and practical application of CE approaches in the mining sector. This is crucial for advancing CE implementation in the sector, which still has a limited knowledge base when it comes to the application of CE principles and approaches.

The empirical findings from Chile's mining sector demonstrates the practical applicability of the proposed framework. The application of various CE approaches by Chile's mining sector, such as the use of desalinated or seawater in ore processing, the repurposing of tailings, and the remanufacturing of mining machinery, have shown that there is significant potential for the mining industry to use CE thinking. However, for CE implementation to have maximum impact, it is essential to design CE approaches in circular configurations that address structural waste in multiple resource states and combine CE approaches from various circularity loops and ROs. These circular configurations have a greater chance of delivering CE practices that drive genuine system change while being economically competitive. Especially when used in the design stage of mining projects, which offers the greatest opportunity to reduce the environmental footprint of a mining project. This proactive approach to design is crucial for ensuring that resource efficiency becomes part of the design of mining industrial processes and allows the sector to align its operations more closely with CE principles. However, the case study also highlights the challenges for the sector to apply CE approaches at scale, particularly when it comes to the prevalent tendencies of a lack of systems thinking and additionality in the design of CE practices.

To conclude, this study uses interviews to explore how mining industry actors conceptualise and apply CE approaches. This method is well-suited to the exploratory nature of the research question, allowing for in-depth insights into practices and perceptions that are not readily observable in quantitative data. Therefore, this research provides a foundation on which future research can build by collecting more systematic data through other study designs. For example, future research could provide a more comprehensive understanding of the sources and material flows of structural wastes through material flow analysis or by using life cycle assessment to study the effectiveness of different CE approaches used in the mining sector.

Nonetheless, the conceptual approach introduced in this paper allows for a system-level analysis of the contexts in which mining firms operate. Such analysis can aid in identifying gaps in existing CE approaches that provide actionable insights and serve as a valuable tool for practitioners in both business and policy. Moreover, while this study uses the context of mining as an exemplary case for the broader discussions on circularity in upstream production systems, the insights are arguably applicable to other upstream industries that supply raw material inputs for the vast global production networks, such as forestry, aquaculture and agriculture. As a result, this study should be seen as a first step towards ensuring that upstream industrial systems are fully integrated into the CE paradigm. Future research should continue on this path by exploring the potential of applying CE approaches in mining and upstream industries while also developing new conceptual tools to guide practitioners in developing circular practices that can help to make raw material extraction as environmentally benign as possible.

6. Exploring the spatial dynamics of circular economy transitions: insights and lessons from Chile's mining territories

Author

Konstantin Born

Highlights

- Investigates the impact of spatial dynamics on circular economy transitions in mining regions.
- Identifies the role of spatial factors in advancing regional circularity.
- Examines how economic enclavism hinders local application of circular practices.
- Highlights the importance of local linkages for circular economy transitions.
- Recommends targeted development strategies to foster regional circularity

Abstract

This paper investigates the spatial dynamics of Circular Economy (CE) transitions in mineral resource-dependent regions. The research addresses a gap in the CE literature's understanding of the influence of spatial factors in CE transitions, which is dominated by empirical studies of industrialised regions with mature industrial ecosystems. As a result, our current understanding of CE transitions arguably relies heavily on cases with spatial configurations of economic activities characterised by high levels of territorial development and existing industrial agglomerations that exhibit strong linkages. Using Chile's mining territories as a case study, the paper explores how the unique spatial configurations of resource-dependent regions influence their ability to transition to more circular modes of production. These regions are often characterised by economic enclavism and weak local linkages, which shape their ability to transition to more circular modes of production.

Through semi-structured and focus group interviews with industry leaders, policymakers, and academics, the study identifies three distinct spatial dimensions that impact regions' ability to apply CE approaches: (1) the configuration of physical infrastructure and production locations; (2) the prevalent value system and patterns of cooperation; (3) the diversity of regional

industrial capabilities and production networks. The study concludes that overcoming spatial and institutional barriers in enclave economies is essential to fostering sustainable industrial ecosystems and accelerating CE transitions. It contributes to the literature on the spatial dimensions of sustainability transitions and advocates for targeted regional development strategies to promote circular practices in resource-dependent areas.

Keywords: Circular economy, Economic geography, Resource-dependent regions, Enclave economy, Mining, Regional development, Chile

1. Introduction

The global shift towards a net zero economy, catalysed by the 2015 Paris Accord, has intensified the demand for renewable energy technologies, which are significantly more material-intensive than traditional fossil fuel-based systems (Hund et al., 2020). It is forecasted that meeting this demand will substantially increase the demand for so-called 'critical energy transition minerals' (e.g. copper, lithium, nickel, cobalt, rare earth elements) (IEA, 2021). Over the past two decades, the concept of the circular economy (CE) has emerged as a promising solution to reduce the reliance on extracting virgin primary minerals to provide these raw materials. Its name highlights what is to be rejected, the currently prevailing linear 'take-make-waste' economy, and instead proposes an economic system that prioritises material efficiency, minimises waste and is intentionally regenerative (de Jesus and Mendonça, 2018; EMF, 2012).

However, while evidence suggests that CE strategies are crucial to reducing society's resource demands, they are insufficient to reverse the need for increased primary resource extraction activities in the short- to medium-term (Bianchi and Cordella, 2023; Born and Ciftci, 2024). As a result, we will likely not only see the expansion of extraction activities in regions currently producing minerals but also see many regions become large-scale mineral producers for the first time.

Despite this growing understanding of the need for continued primary material extraction, there has been an underlying assumption in the CE discourse that raw material extraction activities can eventually become obsolete (Cullen, 2017; Haas et al., 2020). As a result, the CE literature has arguably not paid enough attention to the potential of CE approaches in mitigating the significant environmental challenges of large-scale extractive industries. Therefore, CE transitions in regions heavily dependent on and built around the extraction and exportation of natural resources have received limited attention. Most empirical research on the CE has instead concentrated on a limited range of geographies and sectors: (1) mature industrialised countries (Merli et al., 2018) and (2) sectors in the downstream of global value chains relevant to regions with high material consumption, such as recycling and reuse of end-of-life products (Ragossnig and Schneider, 2019; Schöggl et al., 2020).

Thus, our current understanding of CE transitions arguably relies heavily on cases with *spatial configurations*[19] of economic activities characterised by high levels of territorial development and existing industrial agglomerations that exhibit strong territorial and regional linkages – the opposite of most resource-rich regions. Resource-rich regions have been shown to display very different *spatial configurations* compared to regions with more diversified economic activity (Bridge, 2008). These territories often function as *economic enclaves*, relying on few large firms, displaying high levels of specialisation in one activity, and lacking local economic integration, which limits the development of robust linkages and diverse economic activities (Phelps et al., 2015). These spatial configurations differ significantly from those shown to support CE transformations, including strong inter-firm networks, institutional

[19] In economic geography, spatial configuration refers to the arrangement and distribution of economic activities, resources, and networks across geographical spaces, influencing patterns of trade, investment, and development (Anderson, 2012; Krugman, 2011).

support, and industry concentration that aid in the flow of information, materials, and energy (Ström and Hermelin, 2023).

Therefore, current research on CE transitions may overlook important spatial factors that influence the feasibility and potential of CE transitions in regions and socio-economic settings that differ from the widely studied cases. Thus, this paper asks the following research question: *how do regions' spatial configurations of economic activities impact their ability to transition towards a more circular regional industrial system?*

The remainder of this paper argues that applying existing economic geography theory to CE research is critical for understanding the spatial dynamics of territories' transition towards more circular modes of production and consumption. To illustrate this, the paper examines the case of Northern Chile, a region heavily reliant on natural resource extraction that displays the characteristics of an economic enclave but has ambitions to transform its industrial system into a circular *regional industrial ecosystem*[20]. The case study empirically explores how spatial factors, including the existing production linkages shaped by the region's dominant mining sector, influence the ability of these mining-dependent areas to apply CE approaches in their regional industrial production systems.

The next section will describe the current state of economic geographic enquiry into the CE concept and reflect on the need for adding geographic considerations when studying the dynamics of both circular and sustainability transitions more broadly. It will then engage with some core economic geography concepts that can aid researchers in better understanding the spatial dimensions of transitions towards circular industrial production systems. This is

[20] A regional industrial ecosystem, as defined by Korhonen (2001), is a system that fosters an interactive local system based on the system model of natural ecosystems, i.e. a roundput system. The cooperative waste material and waste energy utilisation between local industrial actors reduces not only virgin material and energy inputs but also the waste and emission output of the system. This reduction in the cost of waste management, raw materials, and energy, coupled with the creation of new economic opportunities, underscores the economic benefits of this model while also reducing the environmental impact of the industrial system.

followed by a description of the methodological approach and the findings from the case study of Northern Chile, which presents three distinct spatial dimensions that impact a region's ability to adopt CE approaches: (1) the configuration of physical infrastructure and production locations; (2) the prevalent value system and patterns of cooperation; (3) the diversity of regional industrial capabilities and production networks. This is followed by a conclusion, which highlights this paper's contribution to our understanding of the spatial dimensions of regional sustainability transitions and argues that by strategically managing and developing territorial linkages, regions can optimise economic outcomes, create more sustainable production systems, and build more inclusive and circular regional economies.

2. Spatialising circular economy transitions

2.1. The circular economy and geography

Although there are now well over 200 varying definitions of the CE concept (Kirchherr et al., 2023), the CE can be broadly understood as a transformative approach towards sustainable resource use within planetary boundaries that promises to "slow, narrow and close socioeconomic material cycles by retaining value as long as possible, thereby minimizing primary resource use, waste and emissions" (Haas et al., 2020, p. 1). Although some precursors to the modern-day concept of the CE were first proposed in the 1960s and 1970s, the CE concept in its current form began to receive significant scholarly attention in the 1990s and early 2000s (Calisto Friant et al., 2020; Stahel, 2016). Championed by the growth of new approaches to studying industrial systems, such as industrial ecology and industrial symbiosis, scholars attempted to learn from the efficient resource recycling observed in natural systems and apply them to industrial production systems (Blomsma and Brennan, 2017; Ghisellini et al., 2016). Since then interest has continued unabatedly with more academic articles and grey literature on the CE published every year (Lieder and Rashid, 2016; Merli et al., 2018).

Although the CE concept has gained traction in various academic disciplines, including economics, environmental science, and engineering, there has been a notable absence of investigations into the influence of geographic factors on CE transitions (Geissdoerfer et al., 2017; Korhonen et al., 2018). Several scholars have argued that the role played by spatial contexts in sustainability transitions is often overlooked and, at best, treated as a background variable (Binz et al., 2020; Coenen et al., 2012; Ström and Hermelin, 2023).

This is underscored by the lack of geographic diversity in the empirical CE literature, with most case studies coming from countries with existing industrial agglomerations that exhibit characteristics conducive to CE transformations, such as robust inter-firm networks, strong institutional support and the spatial concentration of industries, which facilitate the flow of information, materials, and energy in a manner that aligns with CE principles (Alcalde-Calonge et al., 2022; Merli et al., 2018). However, the economies of many regions across the globe, mainly those reliant on the extraction of raw materials, exhibit spatial configurations that starkly contrast with the characteristics observed in mature industrialised countries (Bridge, 2008). Thus, the predominant focus on case studies of CE transformations in industrial agglomerations in mature economies arguably leads to a simplification of the varied spatial configurations and development contexts found globally.

This lack of spatial awareness in the CE literature is of particular concern, as virtually all forms of a transition towards more circular modes of production and consumption require increased levels of resource sharing and interaction between economic actors within a given territory to slow, narrow or close material cycles (Ghisellini et al., 2016; Kirchherr et al., 2023). Research on industrial symbiosis and industrial ecology has long highlighted the critical role of localised networks of economic actors in enabling resource sharing, underscoring the importance of linkages and embeddedness within industrial systems (Chertow and Ehrenfeld, 2012; Chertow, 2009; Korhonen, 2001).

However, there is now growing empirical evidence that these insights also apply to scales beyond the hyper-local industrial setting, with regional and national sustainability transitions requiring the spatial re-configuration of territories to facilitate CE practices. Research by Prendeville and Bocken (2017) demonstrates that the establishment of CE practices in a territory is significantly influenced by the creation of complementary networking structures and services, such as sales platforms, product remarketers, remanufacturers and reverse logistic companies. Empirical studies conducted in Italy (Ghisellini and Ulgiati, 2020), Albania (Gura et al., 2023) and Norway (Sutcliffe and Ortega Alvarado, 2021) underpin these findings by highlighting the importance of creating a network of production and consumption actors and targeted regional clusters that enable the efficient circulation of resources and facilitate resource sharing to promote higher levels of circularity. In addition, there is a growing understanding that the spatial dynamics of resource flows and value chains are essential for designing effective circular economy strategies tailored to the unique characteristics of different regions (Bezama et al., 2019; Bressanelli et al., 2022; Ström and Hermelin, 2023).

Thus, it becomes clear that regions' differing economic activities and their spatial configurations, such as the location, types and number of economic actors and the presence and layout of local infrastructure that determines the cost of moving materials, have a large influence on a territory's ability to re-direct and change its resource and material flows. This is particularly relevant for less developed countries, whose economic activity is often significantly more dependent on exploiting natural resources and thus the flow of physical materials, rather than providing services (Barbier, 2019; Cantú et al., 2021).

2.2. Linkages and spatial configurations in resource-dependent regions

There is evidence that territories focusing on export-oriented, specialised production of natural resources display lower levels of local economic integration (Lashitew et al., 2021). As a result, local synergies, economies of scale effects and knowledge spillovers are less prevalent than within more integrated industrial ecosystems (Buur et al., 2013). Regions afflicted by this condition are termed 'economic enclaves'. Phelps et al. (2015) describe these as follows,

> *"an economic enclave can be defined as a physically, administratively, or legally bounded territory whose geography or morphology is intimately related to the following economic characteristics: dependence on one or a few large firms; high specialization in one activity; and weak integration into the local economy, which is used primarily to access some local factors of production." (Phelps et al., 2015, p. 3)*

The main reason for the emergence of these enclaves is their weak *linkages*. Linkages refer to the connections and interactions between different economic actors, sectors, or activities within a particular geographic area (He and Zhu, 2016). The linkage concept has allowed economic geographers to analyse the variations in territories' spatial configurations since it was first developed in the early 1950s to describe the local impacts of capital-intensive resource extraction in low-income countries (Prebisch, 1950; Singer, 1950). In the following decade, the concept became increasingly popular to understand the spatial dynamics of industrial agglomerations, economic growth and firms' location/relocation decision-making (He and Zhu, 2016; Lasuen, 1969; Perroux, 1955). Hirschman (1958) further improved the concept by linking it to existing economic development theory and methodological approaches of input-output analysis by dividing them into two distinct types; (1) backward linkages, which provide goods and services for a firm's production activities, and (2) forward linkages, which refers to a firm's links with customers purchasing its products.

Linkages are critical for the productive development of regions as they connect various stakeholders within a territory, facilitating the flow of information, resources, and technologies. These interactions are crucial for fostering innovation, enhancing productivity, and driving economic growth within a region (Bathelt et al., 2004). Forward and backward linkages ensure that companies are well-integrated into both local and global value chains, providing access to markets, suppliers, and cutting-edge research and development activities. As a result, it has been extensively argued that the *right* combination of linkages is instrumental in the formation and development of so-called *industrial clusters* (Martin and Sunley, 2003; Porter, 2000). These clusters thrive on the principle of co-location, which allows businesses in a territory to benefit from shared resources such as labour, infrastructure, knowledge, and networks. This also applies to the development of CE practices, as linkages are the core enabler for regional resource sharing, which is necessary to promote higher levels of circularity in a given territory (Razminiene and Tvaronaviciene, 2018).

On the flip side, the nature of enclave economies often restricts the development of robust local linkages and diversified economic activities as they struggle to create economies of localisation due to their high degrees of specialisation and export orientation (Phelps et al., 2015). While enclaves were traditionally understood as strictly defined and enclosed areas, like a mining company town or a plantation (Ferguson, 2005; Sidaway, 2007), the more recent literature on enclaves acknowledges that there is a range of modern economic development scenarios that exist between enclaves and agglomerations or where both types coexist within regional or national scales (Arias et al., 2014). There is also growing evidence that production linkages in enclaves develop across multiple scales in a complex, context-specific fashion (Phelps et al., 2015).

Moreover, recent empirical studies have yielded new insights into enclave economies' nature, formation and prevalence in resource peripheries. For instance, there is growing

evidence that it is not just market forces that produce enclaves, but that state interventions, through regulatory and concessionary measures, co-produce enclave economies alongside market dynamics (Côte and Korf, 2018). This interplay between state and market forces can lead to the creation of distinct spatialities that segregate and isolate the extractive zones from their surrounding environments (Kirshner and Power, 2015), which in turn has been shown to impact socio-economic landscapes beyond the immediate zones of production (Lesutis, 2019).

However, the existence of enclaves is also questioned by some scholars, mainly those utilising a Global Value Chain (GVC) and Global Production Network (GPN) approach. These scholars argue that evolving corporate sourcing and value chain dynamics over the last decades have allowed resource-rich regions to grow new regional backward linkages and encourage industrial growth, thereby overcoming their enclave nature (e.g. Bloch and Owusu, 2012; Boire and Nell, 2021; Morris et al., 2012). However, recent empirical studies cast doubt on these analytical 'bright side' tendencies of the GPN and GVC approach. Radley (2020) finds that new dynamics of corporate sourcing – in particular, increasing levels of outsourcing by large multinational mining companies – have contributed little to industrial development in resource-dependent regions, as they predominantly benefit large multinational suppliers. Similarly, Breul and Rivella Diez (2021) and Atienza et al. (2021a) find that extractive industries' value chains still primarily foster new production linkages outside resource-dependent regions (Phelps, 1993; Phelps et al., 2003). Hence, it can be concluded that resource-dependent regions continue to be affected by the formation of economic enclaves and associated weak regional production linkages.

In sum, linkages are crucial to enabling or blocking the facilitation of resource sharing and interaction between economic actors, which are essential to achieving higher levels of circularity. Thus, I hypothesise that the spatial linkage configuration of mining territories impacts their ability to transition to a more circular production system.

3. Methods

3.1. Research approach and study design

This study utilised an intensive study design based on semi-structured interviews with experts and anchored in critical realism (CR). Critical realist philosophy argues that merely describing data is not enough; instead, we must use abduction to infer reason from the data and uncover the underlying causal mechanisms (Fletcher, 2020). Abductive theory generation, a sensemaking process (Weick, 1995), involves the critical, creative step of discovering a generative idea, hunch, or conjecture (Danermark et al., 2001). This idea can later be developed into a theory through logical deduction and tested via empirical induction (Sætre and Van De Ven, 2021).

Therefore, influenced by Fletcher (2017), the study adopted a methodological approach where empirical findings were first identified through coding interview transcripts and notes before engaging in an abduction process in which empirical data were reinterpreted using existing theoretical concepts. This approach enables a nuanced analysis of empirical data, facilitating the identification of emergent themes, which were then integrated with existing theories during coding and analysis. It is particularly suitable for this study, as there is limited existing theory and knowledge about the causal mechanisms affecting CE transitions in *enclaves*, necessitating an initial abductive theory generation process.

The first data collection stage was a comprehensive literature review on the existing understanding of CE transitions in resource-dependent regions and the spatial dimensions of CE implementation. Based on this, an initial theoretical framework and an interview questions guide were developed. In the next step, empirical data was collected through in-depth interviews with business leaders, government officials, and academics. This data was then augmented with secondary information, such as company reports, production statistics and

news reports to enrich the qualitative findings from the interviews. The interviews focused predominantly on the perspectives of businesses and policy-makers since these are believed to be the critical actors in the implementation of CE approaches (Bocken et al., 2017; European Commission, 2014; Kirchherr et al., 2018). Moreover, the responses provided by policymakers and businesses offer a practical account of CE implementation and adoption from a practitioner perspective.

3.2. Interviews

This research is grounded in fieldwork conducted by the author in Chile between February and April 2023. This research is grounded in fieldwork conducted by the author in Chile between February and April 2023. In economic geography, interviews with business executives and government officials are recognised as an effective means to gather insights into the spatial dynamics of firms and their strategic motivations (Breul and Revilla Diez, 2021; Schoenberger, 1991). During the fieldwork, the author conducted 21 semi-structured interviews and 5 focus group interviews with experts from industry, policy and academia (see Table 6.1). These interviews sought to capture a comprehensive and representative view of the mining sector ecosystem in Chile, encompassing national and international lead mining firms, governmental bodies, and international and local mining service providers and suppliers.

#	Position	Organisation	Type	Interview type
1	Executive Director	Supplier	Business	Semi-structured interview
2	Policy-maker	National government	Government	Focus group interview
3	Policy-maker	National government	Government	Focus group interview
4	Policy-maker	National government	Government	Focus group interview
5	Policy-maker	National government	Government	Focus group interview
6	Policy-maker	National government	Government	Focus group interview
7	CEO	Supplier	Business	Semi-structured interview
8	Programme Manager	Development agency	Government	Focus group interview
9	Programme Officer	Development agency	Government	Focus group interview
10	Programme Officer	Development agency	Government	Focus group interview
11	Board member	Lead firm	Business	Semi-structured interview
12	Director	Industry association	Business	Semi-structured interview
13	CEO	Industry association	Business	Semi-structured interview
14	Director	Consultancy	Business	Semi-structured interview

15	Professor	University	Academia	Semi-structured interview
16	Advisor (Technology and Market)	Lead firm	Business	Semi-structured interview
17	CEO	Public-private partnership	Business/ Government	Semi-structured interview
18	Project Leader (Mining)	National government	Government	Semi-structured interview
19	CEO	Supplier	Business	Semi-structured interview
20	Assistant Professor	University	Academia	Semi-structured interview
21	CEO	Public-private partnership	Business/ Government	Focus group interview
22	Director	Public-private partnership	Business/ Government	Focus group interview
23	Manager	Public-private partnership	Business/ Government	Focus group interview
24	Manager	Public-private partnership	Business/ Government	Focus group interview
25	Programme Manager	Development agency	Government	Semi-structured interview
26	Executive Director	Public-private partnership	Business/ Government	Semi-structured interview
27	Head of Sustainability	Lead firm	Business	Semi-structured interview
28	Programme Manager	Consultancy	Business	Semi-structured interview
29	President	Industry association	Business	Semi-structured interview
30	Executive Director	Research institute	Academia	Semi-structured interview
31	Country Director	Lead firm	Business	Semi-structured interview
32	Professor	University	Academia	Semi-structured interview
33	Manager (Sustainability)	Lead firm	Business	Focus group interview
34	Environmental Engineer	Lead firm	Business	Focus group interview
35	Environmental Engineer	Lead firm	Business	Focus group interview
36	Programme Manager	National government	Government	Semi-structured interview
37	Director	National government	Government	Focus group interview
38	Programme Manager	National government	Government	Focus group interview
39	Senior Consultant (Sustainability & Circular Economy)	Consultancy	Business	Focus group interview
40	Consultant (Sustainability & Circular Economy)	Consultancy	Business	Focus group interview

Table 6.1: Overview of interviews

The author used a judgment sampling approach (Wolf et al., 2016) to select interviewees, choosing participants based on their knowledge of Chile's mining sector and/or the development of CE policies or strategies. This non-random selection was facilitated by the author's personal connections, industry events, and professional networking platforms like LinkedIn. Additionally, the author employed snowball sampling, where initial interviewees referred them to other potential participants.

Before conducting the initial interviews, an interview guide was developed to explore the interviewees' understanding of the CE concept, the current state of CE implementation in Chile, and the perceived drivers, barriers, and potential solutions for implementing CE in the Chilean mining industry (see the interview guide in S5. Guide and Sample Questions for Semi-Structured Interviews in the Supplementary Information). The discussions were structured around the industry's spatial layout, production logic, and existing CE practices. Due to confidentiality concerns, only 69% of the interviews were audio-recorded and transcribed, but detailed notes were taken during all interviews.

3.3. Coding and Data Analysis

These notes and transcripts were then coded and analysed with the help of the Nvivo software. I used a 'directed' coding process (Hsieh and Shannon, 2005) that drew on existing theory and literature but also included categories inductively derived from field observations. A list of codes was initially drawn from the literature review and an initial review of the field notes and transcripts. These codes were then changed, eliminated, and supplemented with new codes during the process in a way that allowed the initial theory from which they were drawn to be reformulated as new insights emerged (Gilgun, 2011).

The process started with 28 'provisional' codes - topic-based 'bins' into which information was sorted (Maxwell, 2012). As the coding process evolved, these 'provisional' codes were adjusted in a second coding cycle. Some were added, changed, or removed based on the data and new theoretical categories that emerged in the abductive process. Ultimately, the initial 28 'provisional' codes expanded to 72 (see Table 6.2).

Topic	'Provisional' codes	Final codes
Circular economy understanding	• Circular economy principles • End-state • Mindset	• Circular economy principles • End-state • Mindset • *Reuse/recycling*

Topic	'Provisional' codes	Final codes
		• *Waste hierarchy* • *Material efficiency* • *Geographic differences* • *Waste becomes useful* • *Materials-as-a-service* • *Phasing out extraction* • *Waste reduction*

Barriers to CE implementation	• Cultural
	• Commercial
	• Spatial
	• Regulatory
		• Cultural
		  ○ *Siloed company structures*
		  ○ *Lack of customer interest*
		  ○ *Hesitant company culture*
		  ○ *Limited willingness to collaborate*
		  ○ *Conservative industry culture*
		• Commercial
		  ○ *High costs*
		  ○ *Competitive pressures*
		  ○ *Operational standardisation*
		• Spatial
		  ○ *Long distance to markets*
		  ○ *Lack of diverse industrial ecosystem*
		  ○ *Insular industry structure*
		  ○ *Lack of physical infrastructure*
		• Regulatory
		  ○ *Obstructing laws and regulation*
		• *Cognitive*
		  ○ *Lack of systems thinking*
		  ○ *Lack of CE knowledge*

Drivers of CE implementation	• Cultural
	• Commercial
	• Regulatory
		• Cultural
		  ○ *Conducive industry standards*
		  ○ *Values-driven decision making*
		  ○ *Increased collaboration*
		• Commercial
		  ○ *Customer demands*
		  ○ *Investor demands*
		  ○ *Social licence to operate*
		  ○ *Supplier offerings*
		  ○ *Cost savings*
		  ○ *Higher revenue*
		  ○ *Risk management*
		  ○ *Reduced closure liabilities*
		• Regulatory
		  ○ *Enabling laws and regulation*
		  ○ *Tax incentives*

Actors	• Mining communities • Customers • Government • Investors • Mining companies	• Mining communities • Customers • Government • Investors • Mining companies

Topic	'Provisional' codes	Final codes
	• Suppliers	• Suppliers • *Mining ecosystem* • *Industry associations*

Focus areas for CE strategies	• Energy consumption
	• Carbon emissions
	• Water use
	• Waste/by-products from operations
	  ○ Tailings
	  ○ Tyres
	  ○ Machine parts
	  ○ Organic waste
	  ○ Chemicals
	  ○ Slags
	  ○ Rock waste
		• Energy consumption
		• Carbon emissions
		• Water use
		• Waste/by-products from operations
		  ○ Tailings
		  ○ Tyres
		  ○ Machine parts
		  ○ Organic waste
		  ○ Chemicals
		  ○ Slags
		  ○ Rock waste
		  ○ *Wood pallets*
		  ○ *Grinding balls*
		  ○ *Steel*
		  ○ *Plastics*
		  ○ *Oil & lubricants*
		• *Water desalination*
		• *Air pollution*

Table 6.2: Coding 'bins'

This iterative coding and abductive analysis identified a series of emergent themes, providing a deeper understanding of the spatial dynamics and causal mechanisms shaping circular economy transitions within Chile's mining sector. The following section will first discuss the reasons for choosing Chile as the case before introducing the distinct spatial characteristics of its mining regions.

4. The case of Chile: A mining economy with circular economy ambitions

4.1. Case study selection

Chile was selected as the case study due to its unparalleled role in the global mining value chain as the world's largest copper producer and the second-largest lithium producer placing it at the forefront of discussions surrounding the provision of materials critical for the energy transition. In 2023, Chile accounted for nearly a quarter of the world's primary copper production, with approximately 30% of this production overseen by the state-owned National

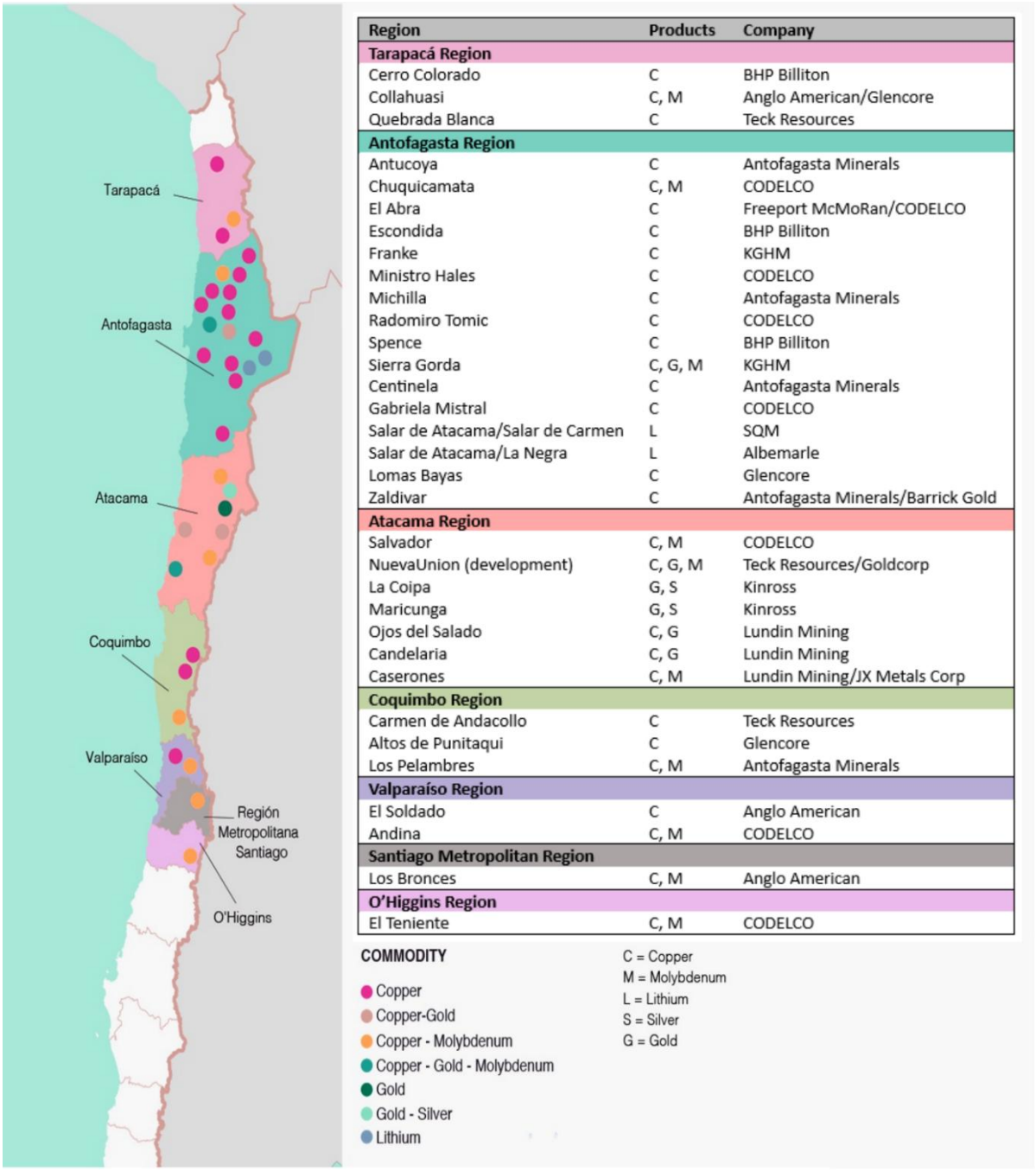
Copper Corporation of Chile (CODELCO), the largest copper mining company by output globally (COCHILCO, 2023b).

Second, the Chilean government has demonstrated a strong commitment to advancing CE, evident through its ambitious roadmap and the passage of significant CE legislation. Moreover, several leading mining companies in Chile have publicly expressed their intention to incorporate CE approaches into their business models. This commitment provides an opportunity to examine the application of CE strategies in a real-world setting, where corporate strategy must align with both environmental objectives and economic realities. Finally, Chile's Northern regions are characterised by resource-dependent economic enclaves with limited local economic integration. This spatial configuration differs from many existing CE case studies, making it a good case study location for an in-depth examination of how spatial factors influence the transition to a CE.

4.2. Case study overview

4.2.1. Northern Chile: A mining enclave

The mining sector's contribution to Chile's GDP and its dominance in the country's export profile are significant, with mining exports constituting 58% of total exports in 2022 and the sector contributing 13.6% to the national GDP (US Department of Commerce, 2023). The sector also employs approximately 175,000 people in Chile. Accordingly, it plays a pivotal role in the economic development, fiscal revenue, and foreign exchange generation of the Chilean state, while also having immense cultural and political power. The heart of Chile's mining industry is the provinces of Antofagasta, Atacama and Tarapacá, located in Chile's arid North with its rich deposits of copper, lithium, gold and molybdenum (see Figure 6.1). The region's mining ecosystem is comprised of several globally leading mining companies and numerous suppliers.



Region	Products	Company
Tarapacá Region		
Cerro Colorado	C	BHP Billiton
Collahuasi	C, M	Anglo American/Glencore
Quebrada Blanca	C	Teck Resources
Antofagasta Region		
Antucoya	C	Antofagasta Minerals
Chuquicamata	C, M	CODELCO
El Abra	C	Freeport McMoRan/CODELCO
Escondida	C	BHP Billiton
Franke	C	KGHM
Ministro Hales	C	CODELCO
Michilla	C	Antofagasta Minerals
Radomiro Tomic	C	CODELCO
Spence	C	BHP Billiton
Sierra Gorda	C, G, M	KGHM
Centinela	C	Antofagasta Minerals
Gabriela Mistral	C	CODELCO
Salar de Atacama/Salar de Carmen	L	SQM
Salar de Atacama/La Negra	L	Albemarle
Lomas Bayas	C	Glencore
Zaldivar	C	Antofagasta Minerals/Barrick Gold
Atacama Region		
Salvador	C, M	CODELCO
NuevaUnion (development)	C, G, M	Teck Resources/Goldcorp
La Coipa	G, S	Kinross
Maricunga	G, S	Kinross
Ojos del Salado	C, G	Lundin Mining
Candelaria	C, G	Lundin Mining
Caserones	C, M	Lundin Mining/JX Metals Corp
Coquimbo Region		
Carmen de Andacollo	C	Teck Resources
Altos de Punitaqui	C	Glencore
Los Pelambres	C, M	Antofagasta Minerals
Valparaíso Region		
El Soldado	C	Anglo American
Andina	C, M	CODELCO
Santiago Metropolitan Region		
Los Bronces	C, M	Anglo American
O'Higgins Region		
El Teniente	C, M	CODELCO

Figure 6.1: Location and directory of large-scale mining projects in Chile. Adapted from Consejo Minero (2024) and Global Business Reports (2021)

Despite its importance to the global value chains of copper and lithium, similar to many other countries with a reliance on the extractive industries, Chile's highly specialised mining sector has historically struggled to develop strong local production linkages. In the late 1990s, the Chilean government began to develop targeted policies and programmes to promote *mining clusters*. These programmes attempted to develop new production linkages in mining regions

by upgrading mining suppliers' capabilities and promoting innovation and technology transfer among local firms (Atienza et al., 2016; Bravo-Ortega and Muñoz, 2021).

Despite these efforts, the anticipated transformation of mining regions into dynamic clusters with strengthened territorial production linkages has been largely unfulfilled. Empirical evidence suggests that the sector continues to exhibit enclave characteristics, with limited forward and backward production linkages. Studies by Arias et al. (2014), Atienza et al. (2016, 2021a, 2021b), Phelps et al. (2015), and Bravo-Ortega and Muñoz (2021) highlight the persistent challenges that Chile's mining regions face, including weak production linkages, a thin labour market, and limited knowledge spillovers in the producer regions. Their findings also point to a downward trend in national and local forward and backward linkages.

While the capital region of Santiago has emerged as a hub for some knowledge-intensive mining services to multinational mining companies active in Chile, fostering some degree of agglomeration economies, the knowledge-intensive aspects of the mining value chain remain concentrated in the capital rather than in the producing regions (Phelps et al., 2015). This geographic concentration of high-value activities in Santiago, as opposed to the mining regions, further exacerbates the sector's enclave tendencies and limits the spread of benefits across the country. Moreover, the general staffing practice of a roster system, where workers live at the mine for a specified period before returning home, has favoured commuting from other regions, which further limits the potential for local economic integration and linkage development (Aroca and Atienza, 2011)[21].

[21] This pattern should be understood in the context of both the inhospitable spatial conditions of Northern Chile's mining regions and broader structural trends. Declining transport costs and new organisational practices increasingly separate workers' residences from their workplaces, shaping economic linkages at regional and national scales rather than solely locally.

4.2.2. Chile's circular economy ambitions

Following years of marginalisation under authoritarian rule, environmental protection emerged as a focal point of policy discourse in the 1990s (Madariaga, 2019). The early 2000s marked a pivotal phase for Chile in the context of environmental policy, driven by its aspirations towards accession to the Organisation for Economic Co-operation and Development (OECD). This ambition catalysed a thorough reassessment and strengthening of its environmental institutions and regulatory frameworks. The efforts undertaken during this period resulted in a notable enhancement of the environmental regime, alongside an elevated ambition of the Chilean state in the domains of environmental protection and climate change mitigation (Bergamini and Pérez, 2015).

A recent cornerstone of this policy shift has been the nation's strategic embrace of the CE paradigm. The establishment of a Circular Economy Office within the Ministry of Environment in 2018 laid the groundwork for the formulation of ambitious CE policies. This initiative was further augmented by a collaborative ministerial effort initiated in 2019 that led to the development and publication of the *Roadmap for a Circular Chile by 2040* in 2021 (Ministerio del Medio Ambiente, 2021). One of the key policy tools to drive this strategic ambition is the Extended Producer Responsibility (REP) law (Government of Chile, 2016). By attributing the responsibility for waste management directly to the producers of specific categories of products, the REP law seeks to instigate a paradigm shift towards more sustainable waste management and recycling practices across various sectors.

5. Results and discussion

5.1. The impact of extractive enclavism on the circular economy transition in Chile's mining regions

The policy shift toward the CE paradigm and its associated legislative changes also significantly impacted the mining sector in Chile, as it is by far the largest waste producer in Chile (Cacciuttolo and Atencio, 2022). The interviews uncovered that Chile's mining sector produces waste from mineral processing, such as tailings[22], waste rock and smelter slags, and generates large quantities of several waste categories covered under the REP law, including tyres, lubricants and plastics. The Ministry of Mines is also increasingly involved in CE policy discussions among government bodies. This is exemplified by the integration of CE concepts within the *National Mining Policy* (Ministerio de Mineria, 2022) and the publication of *Circular Economy Indicators in Chilean Mining* by the Chilean Copper Commission (COCHILCO, 2023a).

Coupled with the growing global interest in the CE, these policy changes have led to the CE paradigm gaining significant attention within Chile's mining sector. More than 90% of interview participants noted that this growth in attention has been particularly notable among large-scale mining firms operating in Chile's copper sector. All of these firms have either committed to CE goals, incorporated CE principles into their sustainability strategies or initiated specific CE projects. One senior mining industry executive explained that the CE ambitions of copper mining companies in Chile formed part of a "new story for mining"[23] in light of the world's need for more minerals to decarbonise. Multiple other respondents from lead firms and industry associations echoed this sentiment, with one mentioning that the CE concept is seen by the industry as a "great tool to obtain and maintain social licence to

[22] Tailings are the waste materials left after the target mineral is extracted from ore
[23] Interviewee #7

operate"[24] amid an increasingly complex regulatory climate and fraught relationships with communities in mining territories. Although this rhetorical shift is most prevalent in the copper industry due to its significantly larger waste volumes compared to the lithium industry, lithium miners are also increasingly adopting CE terminology.

Although there is an increasing number of CE projects launched by mining companies in Chile, all respondents highlighted that Chile still faces many barriers to the widespread application of CE approaches in its mining regions (see Table 6.3).

Themes	Sub-themes	Full sample n = 40		Newly emerged barriers	Previously identified by
Cultural	Siloed company structures	7%	(14)	YES	-
	Lack of customer interest	7%	(14)		Mont et al., 2017
	Hesitant company culture	14%	(10)		Kirchherr et al., 2018
	Limited willingness to collaborate	64%	(1)		Mont et al., 2017
	Conservative industry culture	57%	(3)	YES	-
Regulatory	Obstructing laws and regulations	64%	(1)		Rizos et al., 2021
Cognitive	Lack of knowledge of the CE	57%	(3)		Kindström and Kowalkowski, 2014; Rizos et al., 2021
	Lack of systems thinking	36%	(7)	YES	-
Commercial	High costs	14%	(10)		Kirchherr et al., 2018; Mont et al., 2017
	Competitive pressures	14%	(10)		Hina et al., 2022
	Operational standardisation	14%	(10)	YES	-
Spatial	Long distance to markets	21%	(9)	YES	-
	Lack of diverse industrial capabilities	43%	(6)	YES	-
	Insular industry structure	36%	(7)	YES	-
	Inadequate physical infrastructure	50%	(5)	YES	-

Table 6.3: Mentions of barriers: percentage and rank (in brackets)

Many of the barriers identified by interviewees are in line with the barriers present in other industries and geographic contexts (e.g. Hina et al., 2022; Kirchherr et al., 2018). However, over half of the identified barriers were not previously covered in the CE literature. In addition, 4 out of 8 newly emerged barriers were found to be directly related to spatial

[24] Interviewee #12

factors, a theme not covered in great depth in the literature on CE barriers. This suggests that Chile's existing spatial configuration and the prevalent enclave characteristics within Chile's mining industry have a substantial influence on the implementation of CE practices.

According to the relevant economic geography literature, to develop more circular production processes in a region, it is key to establish a *regional industrial ecosystem* in which a network of industrial actors cooperatively works on reducing the whole system's use of resources and generation of waste (Korhonen, 2001). Such a production system requires mutually beneficial interconnections among industrial processes carried out by unrelated industries to equalise the inputs and outputs of the aggregated industrial processes of a particular locality (Henrysson and Nuur, 2021). The types of industrial process-specific resource exchanges between multiple industrial actors include the exchange of industrial by-products among multiple entities to substitute virgin materials in the production cycle, as well as sharing large-scale infrastructure, such as transport, electricity, water, and waste collection infrastructure (Boons et al., 2011). Accordingly, CE implementation requires not only local industrial manufacturing capacity and a diversity of different industrial sectors that can absorb waste products from other industries but also the infrastructure that allows for the cost-efficient transportation of waste materials and sharing of industrial by-products.

The interview results suggest that Chile's mining regions do not display many of these characteristics. Instead, the dominant mining industry perpetuates the development and maintenance of highly insular production systems. As the representative of a mining industry association put it: *"Large-scale mining is something like a UFO – it is coming down in the head of a valley and installing a big industrial operation, which has nothing to do with the territories, with the people and with the logics and the languages that are being spoken*

there.".[25] This separation and insular production logic leads to the well-documented lack of territorial forward and backward linkages in Chile's mining regions. On the one hand, territorial forward linkages in Chile's mining regions predominantly exhibit an export-oriented orientation, channelling commodities into global value chains (GVCs) while exhibiting limited integration into local economies. On the other hand, territorial backward linkages in Chile's mining regions tend to be limited to relatively low-value inputs, such as food and low-skilled labour, while high-value inputs and knowledge-intensive services are often either imported or procured from the major urban centre of Santiago, relegating peripheral locales in mining regions, such as Antofagasta and Iquique, to the status of *backdoor cities*[26].

Thus, I hypothesise that the distinct spatial configuration of Chile's mining territories has given rise to a regional industrial system that will make it challenging to transition to a circular *regional industrial ecosystem* and develop a conducive environment for the application of CE approaches. In particular, three key themes have emerged from the interviews that connect directly to the newly identified *spatial barriers* in Table 6.3. These are: (1) inadequate physical infrastructure and dispersed production locations; (2) the value system and patterns of cooperation present in the mining industry; and (3) the lack of diverse industrial capabilities and production networks. Together, these themes illustrate how enclave dynamics found in Northern Chile's mining regions hinder the application of CE approaches. I will now discuss each of these themes in turn.

5.1.1 Inadequate physical infrastructure and dispersed production locations

This theme corresponds to the spatial barriers of 'inadequate physical infrastructure' and 'long distance to markets' highlighted in Table 6.3. One key enabler for the development of a regional

[25] Interviewee #7
[26] These backdoor cities represent an intermediate type of urban node within a production network that possesses some functions similar to gateway cities, but that fail to either promote territorial embeddedness or capture sufficient value to drive sustainable development (Atienza et al., 2021a)

industrial ecosystem that supports CE practices is a territory's physical infrastructure (Ruth and Davidsdottir, 2009). However, mining's historically prevalent business model to produce raw materials for export with limited local value addition has led to the creation of production systems designed to almost exclusively service global customers with a corresponding physical infrastructure that is not conducive to a transition towards more circular modes of production. Transportation infrastructure in Chile's mining territories is primarily geared towards transporting imported mining inputs, such as mining machinery and processing chemicals (e.g. sulphuric acid), and mineral products between mine sites in the Andes mountains and ports at the coast.

More than 50% of interviewees mentioned that transportation infrastructure in northern Chile is ill-configured to facilitate the sharing of large quantities of by-products and cascade them between different regional actors. Most interviewees believe that the existing physical infrastructure fails to connect local actors. While these findings are similar to the findings of other studies on the barriers to implementing CE practices in the context of less industrialised regions (e.g. Cantú et al., 2021), it stands in stark contrast with empirical studies from Europe or other more industrialised contexts, where economic actors generally do not perceive physical infrastructure as a material barrier to the implementation of CE practices (e.g. Kirchherr et al., 2018). Thus, for mining regions to successfully transition towards the CE, physical infrastructure is even more important than other regions. In particular, mining is not only the largest waste producer by quantity globally (Ayuk et al., 2020), but the large majority of waste produced by the extraction and processing of mined materials that have the potential to be used by other industries, such as construction material from tailings or smelter slags from the copper industry, or salt waste from lithium production, is of low economic value. As a result, these materials need to be regionally cascaded and processed instead of exported, as transportation of low-value waste over long distances is typically uneconomic.

The continued challenge to reuse tailings materials in other industries exemplifies the importance of location and physical infrastructure. Chile has 764 tailings deposits: 110 active, 473 inactive, 173 abandoned, and 8 under construction, storing more than 26 billion tonnes of tailings, the third largest globally (SERNAGEOMIN, 2024). Several interviewees mentioned that most tailing materials are suitable for use in other sectors and that there is strong interest from the construction industry in using tailing materials as input. However, the lack of physical infrastructure and the often peripheral location of mining operations creates large challenges. As one senior executive of a mining industry body explains,

> *"Regarding tailings we can talk about the construction industry. We've been working on this and getting closer to the construction industry. We've been talking with them throughout the last months to see how we can push this forward. What we see from them is that for them, this is a logistical problem. It's an industry of logistics, if they want to use tailings as an asset, distances and logistical connections are very, very important. So if you have a cement maker, close to a tailings dam, that will be very, very relevant. If they're too far and don't have a good logistical connection, it's not convenient and too expensive for them."*[27]

This shows that even if there is a strong commitment from regional economic actors to change their production processes and share waste materials, if a territory's existing transportation infrastructure is only configured for commodity export and not to share and cascade materials regionally, it makes it significantly more difficult for a regional industrial system to put these waste materials to use.

[27] Interviewee #17

5.1.2. The value system and patterns of cooperation present in extractive enclaves

This theme reflects the barriers of 'limited willingness to collaborate' and 'conservative industry culture,' which, while cultural in form, are directly rooted in the enclave spatial configuration of mining operations. Another reason for the poorly integrated physical infrastructure in Northern Chile is the value system and patterns of cooperation present in extractive enclaves. "Limited willingness to collaborate" was the barrier to CE implemenation mentioned by most interviewees (64%). This lack of cooperation can be found in various areas of the mining industry. As a mining consultant explains, *"There isn't sharing in anything. I mean, we don't share transmission power lines, we don't share roads, we don't share as a mining industry."*[28] For example, water infrastructure in Chile's mining territories displays even lower levels of integration than transport infrastructure. Given the arid conditions in Northern Chile, recurring droughts and community concerns over water, mining operations have had to significantly reduce the extraction of continental water. Instead, many operations now utilise saltwater or desalinated water for mineral processing and dust suppression. Despite these challenges, each mining operation constructs its own infrastructure to transport sea water or desalinated water from the coast to its operations. This lack of cooperation reduces opportunities for water savings and increases the cost of providing water, which incentivises mining firms to continue to use scarce continental water reserves (Pagliero et al., 2024).

There are various reasons for this lack of collaboration, but the majority of interviewees highlighted a historically grown culture of non-cooperation in the sector. For example, one interviewee pointed out that,

> *"Mining has always worked as a silo, historically, maybe in the last 20 years that has changed, and particularly in the last five years. But historically, mining was like, I'm*

[28] Interviewee #14

going to be here, let's not talk to each other, let's not bother each other. I'll try my best, I don't really want to talk with you. And I'll do my thing I know better than you. And that's been the mining culture for decades."[29]

This industry culture seems to largely arise from the enclave nature of the mining business model. On the one hand, mining companies see it as a potential risk to share production-relevant infrastructure with other companies. As one mining executive points out:

"Sometimes it is old mindsets, like with this company that we're working with, to bring desalinated water. It requires a lot of collaboration between private companies and [mining] companies are not used to collaborating. They are selfish. We want to buy [water] from a [specialised water] company that has a plant that can supply several [mining] companies. So it doesn't make sense to have 11 desalination plants, one next to the other. The [specialised water] company that we're working with has a project of 8000 litres per second. Because they want to supply human consumption in places in Antofagasta and Calama that don't have access to potable water. And they also want to supply the mines and they want to subsidise the price of human consumption via companies - that is beautiful. And they will bring - or at least could bring - water to five or six different mining companies that need water. And when you talk to these mining companies they say: 'No, I want my own project, I don't believe in them. It's too risky."[30]

On the other hand, the mining industry's customers and suppliers are primarily located outside of the territory, requiring limited local forward and backward linkages beyond basic inputs. This has led to the development of a self-contained, disembedded ecosystem with an insular culture, which has traditionally focused on internal operations and fulfilling contractual

[29] Interviewee #22
[30] Interviewee #31

obligations to global customers rather than fostering broader regional economic development and cooperating with other economic actors on a territorial level.

Although cultural barriers to the implementation of CE strategies and practices have been highlighted by comparable studies in the European context (e.g. Grafström and Aasma, 2021; Kirchherr et al., 2018), the two most mentioned cultural barriers in this study ("limited willingness to collaborate" (64%) and "conservative industry cultures" (57%)) were perceived to be significantly more critical in this context. The results are, therefore, consistent with assertions from the enclave literature that the lead firm-centric characteristics of economic enclaves lead to cultures and business practices that hinder cooperation among firms in the regional industrial system (Arias et al., 2014).

This lack of cooperation and conservative industry culture negatively affect a territory's potential to transition towards a CE in several ways. Firstly, by each mining operation constructing its infrastructure independently, opportunities for resource sharing and optimising infrastructure utilisation are missed. This inefficiency not only increases costs but also exacerbates environmental impacts by encouraging the development of under-utilised infrastructure. Secondly, it limits the potential for knowledge exchange and technology transfer, which in turn leads to a weaker technological ecosystem and a lack of innovation. Despite the potential for regional industrial systems to achieve greater material efficiency through existing technologies, the application of CE practices often necessitates targeted innovation (Brown et al., 2019). This innovation encompasses not only technological advancements but also novel business models facilitating the cost-effective transformation of industrial by-products into valuable inputs for other industrial processes (Lüdeke-Freund et al., 2019).

Several interviewees mentioned that mining companies' hesitant culture leads to a strict focus on maintaining the existing business model by lowering production costs, increasing productivity, and leveraging economies of scale. As a result, mining enterprises often exhibit low internal innovation activity, and most innovation initiatives are spearheaded by large global mining suppliers, with limited contributions from local actors within mining territories. This leads to low levels of regional innovation and knowledge exchange in mining regions. As a mining consultant explains,

> *"Normally the solutions come from outside of companies. Companies, their purpose, their big KPIs are production costs and safety and whoever deviates from those purposes is not complying with the corporate framework. And I think the ones who are leading the thinking on these kinds of solutions are people from the outside. Suppliers, who see eventually in a visit you know, the possibility of business or possibility of offering some service to the mining companies etc. And that's somehow also a difficult thing for the innovation itself in mining, you know, mining companies or mining operations are quite isolated, quite autonomous you know, quite shut for the external world."*[31]

The literature corroborates these findings (Arias et al., 2014; Atienza et al., 2016; Bartos, 2007). This dynamic leads to limited innovation as most global suppliers have little to gain from the localised circulation of materials, as their manufacturing mainly occurs outside mining regions. Moreover, several interviewees noted that mining companies' stringent focus on meeting export production targets leaves local mine-site staff little room to experiment with new technologies or processes within mining operations. Additionally, mining operations entail substantial initial investments and the assets involved often have extended lifespans, increasing

[31] Interviewee #1

the costs and potential risks of innovation. As a result, the testing and implementation of innovative CE solutions face significant obstacles, with most innovation activities targeting incremental improvement of existing industrial processes within the mine gate that neither challenge the mining companies nor their global suppliers' business models.

5.1.3 Lack of diverse regional industrial capabilities and production networks

This theme ties to the barriers of 'lack of diverse industrial capabilities' and 'insular industry structure,' highlighting how spatial isolation limits the development of regional production networks. Previous studies have shown that extractive enclavism impacts the diversity of resource-rich regions' industrial capabilities and the depth of the local production networks (Arias et al., 2014). The findings support this and show that the lack of local forward linkages, a limited industrial base and regional value chains are also present in Northern Chile. 43% of interviewees perceive "the lack of diverse industrial ecosystem" as a critical barrier to adopting CE strategies and practices in the territory. CE strategies, such as extending the life of mining inputs or recovering valuable materials from end-of-life (EoL) mining equipment, require local manufacturing capacity to remanufacture, repurpose or repair equipment and reuse or recycle its high-value components. Thus, Chile's mining territories lack the conditions to effectively reuse even higher-value waste materials, such as mining equipment, grinding balls, tyres and batteries.

For instance, the operation of large ball mills, integral to crushing copper-rich ore, relies on steel grinding balls that undergo wear and necessitate replacement over time. The findings show that these grinding balls are not subjected to recycling and reuse despite their relatively high value, culminating in substantial accumulations at copper mine sites. The key reason for this is both a lack of local grinding ball production and other industrial production that could make use of the large amounts of grinding ball waste. Similarly, a substantial portion of imported equipment arrives at mine sites on wood pallets. Ideally, pallets could undergo reuse,

a common practice in industrial clusters. However, the absence of local production for material requiring palletisation increases the expense of pallet removal. Consequently, many operations resort to on-site pallet incineration.

This shows that without a diverse industrial base and robust local production networks, the potential for reusing and recycling waste materials generated by mining operations is severely limited, often leading to their disposal rather than reuse. Reverse logistics is particularly critical in this context: the collection, transport, and redistribution of bulky or heavy materials—such as tyres, grinding balls, or equipment components—pose significant challenges in remote mining locations, adding costs and limiting circular opportunities. One senior executive at a mining firm explains,

> *"Another aspect is the waste for industrial parts, pallets, boxes, and plastic. And we have made a commitment to reduce [these waste streams by] 50% until 2025. And the main issue there is first of all, you need to work with your providers. Internally of course, you need to put the palette there and then get it to where it can be reused or to recycled. We're doing that now. The second part is who can use these kinds of [waste] elements. And we have some alternatives in Santiago. But there are few alternatives in the North of Chile, in Antofagasta and Iquique. [..] The main challenge is to find a company that can recycle or reuse these kinds of [waste] elements. We work with a company that uses our waste in Santiago. But Santiago is very far from our facilities."* [32]

These insights are consistent with the CE literature, which has shown that a localised network of production and consumption actors that enable the efficient circulation of resources and facilitate resource sharing is essential to promote higher levels of circularity (e.g. Bressanelli

[32] Interviewee #27

et al., 2019; Ghisellini and Ulgiati, 2020). In addition, reverse logistics plays a critical role in enabling circular practices in remote mining regions, highlighting the challenges of transporting materials across long distances to recycling or remanufacturing facilities.

One pathway to address a lack of regional industrial capabilities is policy intervention and regulation. Although all interviewed industry representatives perceived the government as not being active enough in incentivising the application of CE approaches, and the impact of regulatory barriers was mentioned by many interviewees (64%), the large majority of existing CE practices in the mining sector in Chile are concerned with waste categories regulated under the REP law. Moreover, 80% of interviewees mentioned that the REP law has significantly influenced the implementation of CE practices in Chile's mining sector. In particular, the recycling and reuse of EoL tyres has received considerable attention, as the mining industry is now obliged to recycle 25% of its EoL tyres and store at least 50% of them (Moore, 2023). By 2030, all EoL tyres must be fully recycled or reused. It is estimated that an average large-scale mine in Chile uses around 3,000 tonnes of tyres annually (Weibold, 2022). For example, Escondida, the world's largest copper mine, uses over 160 haul trucks, each requiring six tyres weighing over 5 tonnes each.

This pressure is starting to lead to the development of new territorial forward linkages and industrial capabilities for managing waste generated at mine sites. For instance, the inauguration of Northern Chile's first tyre recycling facility in Coquimbo in early 2024 exemplifies a tangible step towards increased circularity and can be directly attributed to the introduction of the REP law. Nonetheless, the efficacy of such initiatives is contingent upon several factors, including the availability of local processing infrastructure, proximity to recycling facilities, the diversity of industrial actors capable of utilising recycled materials, and the regulatory framework that supports material recovery and reuse. Presently, these policy mechanisms primarily address relatively high-value materials, as the territory lacks both the

physical infrastructure necessary to facilitate the circulation of substantial quantities of low-value waste materials and a diverse array of non-mining industrial entities capable of integrating these materials into their production processes.

5.2. Implications

The findings highlight how spatial configurations of economic activities shape Chile's regional industrial system by influencing its infrastructure configuration and defining the value systems, cooperation patterns, regional industrial capabilities and production networks facilitating material exchanges. Although the regional industrial system of Chile's mining territories exhibits unique characteristics that affect CE practices, the case study offers insights into transforming existing regional industrial systems into regional industrial ecosystems that support the application of circular approaches. These observations lead to five key implications for understanding the spatial dimensions of CE transitions.

First, inadequate infrastructure and the geographic location of production facilities can significantly hinder CE transitions. For instance, the transportation infrastructure may lack the necessary connections to efficiently move low-value waste materials between different industrial entities. Similarly, other physical infrastructures, such as water and energy systems, may not be optimised for regional resource sharing. As a result, material circulation and by-product exchange required to support CE practices and a broader CE transition are constrained. These spatial constraints also have direct economic implications, as transporting heavy or bulky materials over long distances increases operational costs and reduces the financial feasibility of circular practices. Therefore, analysing the existing infrastructure configuration and the geographical location of production facilities is crucial when studying CE transitions, as the right type of infrastructure is essential to support resource sharing and the efficient exchange of by-products.

Second, regional production networks act as conduits for the flow of materials and products between industrial actors, facilitating exchanges that enable circular production processes. Particularly important are market networks connecting unrelated value chains or different stages of a value chain, fostering synergies and collaboration that support circular practices (Henrysson and Nuur, 2021). In contrast, regions with underdeveloped market networks and limited industrial capabilities may face material exchanges and collaboration constraints. In Chile's mining regions, the history of enclavism has resulted in an immature, undiversified market network that limits the transformation of mining waste into valuable by-products for other local economic actors. Hence, it can be concluded that without a diverse range of market actors representing various industries, there are fewer opportunities for by-products to be reused or recycled within a region.

Third, value systems and patterns of cooperation deeply influence the development of new linkages within regional industrial systems, affecting a region's capacity to transition to more circular production practices. As a result, historical norms, attitudes towards collaboration, and resource sharing play a critical role in determining the feasibility and effectiveness of circular strategies and practices. These norms and attitudes are deeply ingrained in the cultural fabric of industries and regions, shaping interactions between companies, government entities, communities, and other stakeholders. It follows that in regions where cooperation and open dialogue have been the norm, there may be a more fertile ground for developing innovative CE practices that require the collaboration of multiple actors across different sectors. However, collaboration and resource sharing face significant challenges in historically insular sectors like mining, where cultural norms are characterised by risk aversion, individualism, and a focus on internal efficiency and export targets. As a result, regions with enclave characteristics arguably face significant challenges in developing the linkages essential for a successful transition towards a CE.

Fourth, internal innovation impetus within enterprises is often limited in regions where innovation is primarily driven by external forces and the industrial landscape is dominated by one type of activity (Pietrobelli et al., 2018). In these contexts, firms often focus on maintaining the status quo rather than investing in new technologies and practices supporting CE transitions. This challenge is particularly pronounced in the extractive sector, where reliance on large-scale, capital-intensive operations with long asset lifespans creates a risk-averse environment resistant to adopting new technologies or processes that could disrupt existing production systems or require significant upfront investments. While such tendencies are widely documented in sustainability transitions literature (e.g. Geels, 2002; Smith et al., 2010), they are intensified in Chile's mining regions due to their enclave characteristics, limited local industrial diversity, and the isolation of mining operations, which further discourage experimentation with circular practices. Thus, it can be argued that regions must cultivate a dynamic technological ecosystem, where innovation is not just imported but is also organically grown through local initiatives and collaborations, to stand a better chance at successfully transitioning towards CE practices. This requires creating conducive environments for innovation that encourage not just incremental technological advancements of existing industrial practices but also the development of new industrial approaches and novel business models that facilitate cost-effective recycling, reuse, and repurposing of materials.

Finally, the case presented in this paper also shows that developing a more nuanced understanding of the impact of distinct *spatial configurations of economic activity* in regions is highly relevant to promoting successful transitions towards higher levels of regional circularity. It shows that the remoteness and physical separation of industrial operations can create a 'tyranny of distance' that impedes the development of circular material flows and by-product sharing by limiting the potential for efficient material exchanges between different industrial actors. These spatial barriers are further exacerbated in territories with

underdeveloped or proprietary transportation infrastructure systems. Moreover, the discrete nature of corporate production systems in some sectors, characterised by large multinationals with proprietary technologies and preferred suppliers, creates additional hurdles for establishing the collaborative networks necessary for CE implementation in these regions.

6. Conclusion

Circular transitions in regions heavily reliant on extractive industries, exemplified by Chile's mining regions, illuminate the complexities and potential pathways for integrating sustainability within historically linear economic models. It also highlights the systemic challenges such regions face in transitioning towards more sustainable production systems. This study illustrates that the entrenched enclave characteristics of the Chilean mining industry, characterised by a focus on export-oriented production of a small range of commodities with minimal local value addition and integration, have historically limited the development of robust local production linkages necessary for a more circular and sustainable industrial ecosystem.

As a result, it becomes clear that the transition to a CE in such contexts is not merely a matter of implementing new technologies or recycling practices but requires a fundamental shift in the underlying economic and industrial structures. In mining regions, the combination of capital-intensive operations, geographically isolated sites, and limited local industrial diversity makes the development of circular practices particularly challenging. The lack of forward and backward linkages, industrial symbiosis opportunities, and local processing infrastructure amplifies the difficulty of implementing CE strategies, beyond what is typically required in other sectors. This shift entails fostering more territorial forward and backward linkages that can facilitate the development of physical infrastructures, deeper market networks and a culture of collaboration and innovation that supports circularity. This paper’s findings

suggest that the success of such a transition depends on addressing the specific challenges posed by enclave economies, including the lack of diversified economic activities, the insular mindset of key industry players, and the historical neglect of developing a regional industrial ecosystem and local value chains.

These findings also raise crucial questions for regional development and CE transitions more broadly. The interest of both private-sector firms and governments in being seen as actively working to implement circular practices presents a window of opportunity to develop the enabling conditions for a transition to a CE. However, if the transition to a CE is to be realised, it will require strengthening local industrial capabilities and developing new physical infrastructure to support greater local development and resource sharing. Thus, targeted intervention can support regions in creating a more conducive environment for a CE transition by strategically managing and developing territorial linkages. For example, regulatory frameworks and policy incentives can encourage firms to adopt circular practices, reduce waste, and implement sustainable production processes.

Initially, the process may start by promoting the slowing or narrowing of material loops within the existing regional industrial system. In mining regions, this includes repurposing old mining waste as inputs for other industries or reusing and recycling EoL mining equipment. However, beyond merely managing existing waste and promoting recycling, it is crucial to critically examine and address the production processes and material loops that generate large amounts of waste in the first place. Consequently, if targeted interventions can effectively promote CE practices, the transition to a CE can go beyond environmental necessity and become a strategic opportunity to uplift peripheral regions and open up new pathways for the sustainable development of mining regions.

I have demonstrated that the insights from this case study provide a valuable contribution to our understanding of the spatial dimensions of regional transitions towards CE and sustainability transitions more broadly. In addition, this paper makes a contribution to the broader debates in economic geography by offering a new, slightly more critical perspective to the study of CE transitions that aims to correct an arguable analytical in-built bright side bias of some of the existing literature on CE transitions. This perspective can help both policymakers and scholars navigate the complexities of developing interventions to transition regions towards higher levels of circularity. Specifically, the study advances the literature by highlighting how spatial factors, such as infrastructure configurations, the geography of production networks, and the enclave characteristics of mining economies, shape both the opportunities and constraints for circular transitions, thereby connecting empirical insights from Northern Chile to broader debates on the spatiality of sustainability transitions.

However, pertinent questions about the generalisability of these findings to other regions with different policy environments, economic activities, and levels of industrialisation remain. Therefore, future research could benefit from investigating other understudied geographical contexts and sectors and building on the insights from this work to develop a more nuanced understanding of the spatial dimensions of CE transitions in geographic contexts that lack the more advantageous spatial enabling environment for CE transitions that characterises the majority of the existing empirical examples in the CE literature.

7. Conclusion

This thesis set out to explore the limitations of our existing understanding and approaches to CE transitions in the context of critical energy transition mineral extraction and offer novel conceptual and practical insights into the mining sector's role in the transition towards more circular modes of production and consumption. By employing a mixed-methods approach grounded in critical realism, this research has sought to bridge the gap between theoretical conceptualisations of the CE and the practical realities of its implementation in upstream value chain segments.

The investigation began with an analytical literature review that uncovered the existing CE literature's weaknesses in addressing the mining sector's unique context, showing the need for a more holistic approach to CE that encompasses upstream value chain segments. This was followed by a quantitative assessment of the limitations of the CE literature's current focus, establishing the continued necessity of primary mineral production to meet the growing demand for critical energy transition minerals. Building on this foundation, the research delved into the conceptual and practical challenges of applying CE approaches in mining operations and resource-dependent regions through two qualitative studies.

This approach has allowed for a nuanced examination of the key dimensions that shape CE transitions in the mining sector. Furthermore, it discussed the challenges and opportunities of applying CE approaches in the mining sector and its host territories, offering initial insights into the role of place-based factors in shaping circular economy transitions in the context of less industrialised regions.

Given the paper-based structure of this thesis, each of the empirical chapters already contains its own conclusion. Therefore, after a quick recapitulation of the principal findings of each empirical chapter, this final chapter aims to draw higher-level findings from the overall

research project. The remainder of this chapter will be structured as follows: first, it will summarise the key findings and contributions of the research before discussing the theoretical and practical implications of these findings. It will then reflect on the project's limitations and suggest avenues for future research before concluding with some closing remarks on the significance of this work and thoughts on the future of CE adoption in the mining sector.

7.1. Principal findings

This section will summarise the key findings from the analytical literature review and the three empirical articles presented in Chapters 4, 5, and 6. These findings collectively address the overarching research questions posed in Chapter 1: (1) What is the mining sector's role in the transition towards a more circular economy?; and (2) What place-specific mechanisms and structural conditions enable or inhibit circular economy transitions in the mining sector and its host regions?

Table 7.1 gives a high-level overview of the objectives and findings of each of the three empirical chapters. The following subsections will discuss the chapters' principal findings, highlighting their contributions to our understanding of circular economy adoption in the mining sector and resource-dependent regions.

	Chapter 4: The Limitations of End-of-life Copper Recycling and its Implications for the Circular Economy of Metals	**Chapter 5: Application of Circular Economy Approaches in the Mining Sector: Evidence from Chile**	**Chapter 6: Exploring the Spatial Dynamics of Circular Economy Transitions: Insights and Lessons from Chile's Mining Territories**
Objectives	Evaluate the potential of EoL recycling strategies to meet future metal demand and replace primary production.	Investigate the current state of CE adoption in the mining sector and identify potential CE strategies to address sectoral sustainability challenges.	Examine the role of space and spatial configuration of economic activity in enabling CE adoption in resource-dependent regions.
Scale	Global	National (Chile)	Regional (Northern Chile)
Research Questions Addressed	**RQ1:** How does the forecasted demand for critical energy transition minerals impact the ambition of transitioning to a circular economy?	**RQ3:** What is the existing understanding of the role of critical energy transition minerals' extraction in a circular economy?	**RQ6:** What are the barriers and enablers for circular economy transitions in mineral resource-dependent regions? **RQ7:** How does the spatial

	RQ2: What are the limitations of downstream CE strategies for critical energy transition minerals sourcing?	**RQ4:** What role can CE strategies and practices play in making primary mineral extraction processes more responsible? **RQ5:** How can circular economy principles, strategies and practices be integrated into primary mineral extraction processes?	configuration of economic activity in mineral resource-dependent regions affect their ability to transition towards a more circular regional industrial ecosystem?
Key Findings	1) End-of-life (EoL) recycling strategies alone are insufficient to meet future metal demand for the energy transition. 2) There is a need for alternative circular economy (CE) strategies beyond EoL recycling. 3) Mitigating the harmful impacts of primary metal production by adopting CE principles in the mining sector is crucial.	1) Current CE frameworks lack applicability to mining and other upstream industries. 2) Three new conceptual elements were identified for system-level analysis of CE adoption in the mining industry. 3) The study mapped existing CE strategies and practices deployed in Chile's mining sector.	1) Unique spatial configurations of resource-dependent regions (e.g. dispersed production locations and lack of infrastructure) influence their ability to transition to more circular regional industrial ecosystems. 2) Economic enclavism and weak local linkages shape the ability of these regions to adopt more circular modes of production. 3) Three distinct spatial dimensions impact resource-dependent regions' ability to implement CE approaches.
Implications	• A broader approach to circularity is needed, focusing on integrating CE thinking into industrial mining production systems. • Primary production and extraction of minerals will remain necessary in the short- to medium-term despite increased circularity in downstream value chain segments.	• There is potential for CE strategies and practices to address some of the mining sector's sustainability challenges. • The mining sector faces significant challenges in adopting CE principles, strategies, and practices at scale.	• Geographic considerations need to be added to conceptual frameworks used to study circular transitions and sustainability transitions. • Overcoming spatial and institutional barriers in enclave economies is essential for fostering sustainable regional industrial ecosystems and advancing CE transitions in resource-dependent regions.

Table 7.1: Overview of findings

7.1.1. Chapter 4

The study presented in Chapter 4 examined the potential of end-of-life (EoL) recycling strategies to meet future metal demand and reduce the need for primary metal production.

Using a novel dynamic probabilistic material flow analysis (DP-MFA) model applied to copper, a key critical energy transition mineral, the research revealed several significant findings.

Firstly, Chapter 4 demonstrates that EoL recycling strategies alone are insufficient to meet the projected demand for copper in the coming decades. The model results showed that even under optimistic scenarios with high recycling rates, the supply of secondary copper from EoL products would fall significantly short of meeting the growing demand driven by the energy transition and other factors. The analysis showed a high likelihood that copper demand in 2050 will exceed what EoL recycling can supply, requiring increased primary copper production compared to current levels in the large majority of modelled scenarios. Therefore, even with considerable advances in recycling technology and scrap collection efforts, dozens of new copper mines would have to be opened to increase primary metal extraction and replace the anticipated decreases in production from existing operations over the next 30 years.

Secondly, Chapter 4 shows that the limitations of EoL recycling strategies are not unique to copper. Considering the comparatively high recycling rate for copper and the substantial existing in-use stock, the inability of secondary supply to fully replace primary production for copper raises serious concerns for other critical minerals required for the energy transition, most of which have significantly lower existing in-use stocks and lower available recycling capacities. Therefore, it suggests that EoL recycling as a CE strategy will likely encounter even more significant constraints with other energy transition minerals, such as lithium.

As a result, the Chapter highlights the need for more integrated thinking about circularity throughout the entire value chain. While EoL recycling remains a critical component of any CE transition, it is evident that a more comprehensive approach is necessary to address the challenges of meeting future demand for critical energy transition minerals. This includes

applying CE principles, strategies and practices to industrial mineral extraction systems in order to mitigate the potential environmental and social impacts associated with the primary production of critical energy transition minerals.

7.1.2. Chapter 5

Chapter 5 is built upon the foundation laid in Chapter 4 and explores the potential application of CE thinking to the mining sector. The Chapter revealed that existing CE research has been predominantly focused on the application of CE approaches in downstream value chain segments, rather than on upstream raw material extraction activities. In addition, it showed that the mining sector faces distinct complexities compared to downstream industries, making it essential to develop specific tools that facilitate systematic assessments to identify targeted CE approaches that address these unique complexities and challenges. Consequently, the Chapter identified three conceptual elements that can help in the design and application of appropriate CE approaches in the mining sector: (1) a clear communication of the *goal and boundary* of the industrial production system that the application of CE approaches is targeting; (2) an identification of the *source and type of inputs* used by the system; and (3) a consideration of the *resource state* of these inputs and the subsequent structural wastes generated from them.

To test the practical applicability of this hypothesis, I used these conceptual elements to map CE approaches in Chile's mining sector. This mapping exercise demonstrated the practical applicability of the conceptual elements within the context of the mining sector and revealed the ongoing application of various CE approaches in Chile's mining sector. Examples include the use of desalinated or seawater in ore processing, the repurposing of tailings, and the remanufacturing of mining machinery.

These findings indicate significant potential for the mining industry to apply CE thinking. However, the research also uncovered a trend of companies rebranding existing

sustainability efforts as CE approaches rather than developing new ones. This rebranding trend reflects a desire within the mining industry to be perceived as leaders in applying CE approaches. While this can be seen as a positive step in raising awareness and aligning with contemporary sustainability paradigms, it also raises questions about the additionality of CE practices.

Finally, the chapter emphasised that to apply CE approaches in the mining sector to reduce environmental harm and maximise positive benefits effectively, it is vital to combine multiple CE strategies and address structural wastes in different resource states.

7.1.3. Chapter 6

Chapter 6 revealed significant limitations in our current understanding of the impact of place-based, spatial factors on CE transitions. The existing body of research on CE transitions predominantly relies on case studies from regions characterised by high levels of territorial development and established industrial agglomerations with strong territorial and regional linkages. The Chapter showed that this focus overlooks crucial spatial and economic factors that influence the feasibility and potential of CE transitions in regions with different socio-economic settings, such as those heavily reliant on resource extraction.

Using the case of Northern Chile's mining territories, the chapter highlights how economic and spatial factors shape a region's configuration of economic activities, defining its value systems, cooperation patterns, regional industrial capabilities, and production networks that facilitate material exchanges. Three key spatial dimensions emerged as critical factors influencing the potential for regional CE transitions.

Firstly, it showed that the existing transportation infrastructure and the geographic location of production facilities, and the high costs of reverse logistics significantly impact CE transitions. Infrastructure is crucial in supporting CE approaches, as material circulation and

by-product exchange are key to increasing a territory's circularity. However, as many resource-dependent regions are characterised by inadequate infrastructure, dispersed production locations, and high transport costs, they face a distinct disadvantage in applying CE strategies and practices compared to territories with stronger regional linkages.

Secondly, Chapter 6 highlighted that regional production networks act as conduits for the flow of materials and products between industrial actors, as market networks connecting unrelated value chains or different stages of a value chain are crucial to support higher levels of circularity. However, the history of enclavism in resource-dependent regions has resulted in immature, undiversified market networks that limit opportunities for by-products to be exchanged and valorised, and which constrain the economic viability of CE approaches.

Thirdly, Chapter 6 showed that value systems and patterns of cooperation deeply influence the development of new linkages within regional industrial systems. Collaboration and resource sharing face significant challenges in historically insular sectors like mining, where cultural norms are characterised by risk aversion, individualism, and a focus on internal efficiency and export targets. Consequently, regions with enclave characteristics arguably face significant challenges in developing the linkages essential for a successful transition towards a CE. As these linkages are crucial for cycling by-products, there is less fertile ground for developing innovative CE practices that require the collaboration of multiple actors across different sectors in resource-dependent regions.

Finally, the chapter highlighted the systemic challenges regions heavily reliant on extractive industries face in transitioning towards more sustainable production systems. It showed that transitioning to a CE in such contexts is not merely a matter of implementing new technologies or recycling practices but requires a fundamental shift in the underlying economic and industrial structures. This shift must entail the development of more territorial forward and

backward linkages that can facilitate the development of physical infrastructures, reduce logistical costs, broaden market networks, and foster a culture of collaboration and innovation that supports circularity. Consequently, by addressing these spatial dynamics, resource-dependent regions can potentially overcome the barriers to CE transitions and move towards more sustainable and circular economic models.

7.2. Overarching findings and contributions to the literature

This thesis contributes to our understanding of the CE in the context of mining and resource-dependent regions, as well as the fields of circular economy research, economic geography and sustainability transitions research. While prior research on the CE has provided valuable perspectives on downstream value chain segments and resource-consuming regions, the role of upstream resource extraction and resource-dependent regions has received comparatively limited attention. By drawing on perspectives from economic geography and sustainability transitions, and applying them to the Chilean mining industry, the thesis adds empirical evidence from extractive industries to these debates and demonstrates how CE approaches can be applied in sectoral and territorial contexts that differ from the more commonly studied downstream industries and industrial clusters.. In particular, using the example of Chile's mining regions, it demonstrates how the specific circumstances and conditions found in the mining sector and its host regions shape the opportunities and limitations for applying CE approaches in this context.

The findings of this thesis can be grouped into three areas of contribution. The first two address the first overarching research question (what is the mining sector's role in the transition towards a more circular economy?) by establishing the continued need for primary mineral production alongside downstream CE strategies and demonstrating how existing CE frameworks can be extended to capture the distinctive circumstances of the mining sector. The

final finding addresses the second overarching research question (What place-specific mechanisms and structural conditions enable or inhibit circular economy transitions in the mining sector and its host regions?) by showing how enclave economies and weak territorial linkages constrain circularity in resource-dependent regions. I will now discuss each of the three overarching findings in turn.

Firstly, Chapter 4 provides a robust analysis of the contribution of secondary copper production to projected demand to 2050. The results demonstrate that even under optimistic recycling scenarios, end-of-life copper recovery cannot substitute for primary production. This builds upon work to estimate the potential of CE strategies to supply copper for the energy transition (e.g. Ciacci et al., 2020; Elshkaki et al., 2016; Watari et al., 2022), demonstrating, through a novel probabilistic treatment of uncertainty, that downstream strategies alone cannot meet the material needs of the energy transition. This provides additional evidence to temper overly optimistic assumptions about CE's substitution potential in global supply chains that have been pointed out by other scholars previously (e.g. Cullen, 2017; Haas et al., 2015).

Secondly, Chapter 5 explores the application of CE thinking in the Chilean mining sector. The chapter demonstrates how CE frameworks can be adapted to capture the distinctive circumstances of the mining sector. Empirically, it shows how companies apply CE approaches such as tailings valorisation, seawater use, and equipment remanufacturing. It also highlights the rebranding of existing sustainability efforts as CE practices, echoing critiques of CE's conceptual stretching (e.g. Corvellec et al., 2022; Haas et al., 2020; Kirchherr et al., 2023; Kirchherr and van Santen, 2019; Korhonen et al., 2018), but demonstrates this dynamic in a new sectoral and geographic context.

Thirdly, the findings from Chapter 6 advance understanding of the spatial dynamics of CE transitions by examining Northern Chile's mining territories. While existing CE transition

studies often focus on industrial clusters in advanced economies (Ghisellini et al., 2016; Merli et al., 2018; Razminiene and Tvaronaviciene, 2018), this thesis shows how enclave economies with limited diversification, weak infrastructure, and fragile local networks face systemic barriers to circularity. The findings nuance current debates on the impact of spatial characteristics on the application of CE approaches (e.g. Andersen et al., 2022; Domenech et al., 2019; Kulczycka et al., 2020; Ström and Hermelin, 2023) by emphasising how industrial operations located within mining enclaves, with weak forward and backwards linkages, shape the feasibility of applying CE approaches, such as by-product exchange, reverse logistics and industrial symbiosis.

7.2.1. Contributions to circular economy, economic geography and sustainability transitions research

With these findings, the thesis makes several interrelated contributions to circular economy (CE), economic geography, and sustainability transitions research. Each contribution arises from addressing an underexplored dimension of CE transitions: the role of primary extraction and resource-dependent regions in shaping the possibilities and limits of circularity. By situating the case of Chilean mining within these debates, the thesis demonstrates the relevance of existing theoretical frameworks while showing how they need to be adapted and extended when applied to the mining sector and resource-dependent regions.

Contributions to circular economy scholarship

The thesis advances the CE literature by explicitly foregrounding the upstream segment of global value chains and resource-dependent regional contexts, areas that have remained underexplored in existing research. It does this by addressing three interrelated dimensions: the future potential of CE to reduce primary resource demands, the practical application of CE

approaches within the mining sector, and the critical importance of considering mining's unique geographical and spatial contexts.

First, by applying a dynamic probabilistic material flow analysis to copper, the thesis provides a more nuanced understanding of the capacity of downstream CE approaches to alleviate primary resource extraction pressures. The findings in this thesis indicate an ongoing need for expanding primary mining capacity despite enhanced circularity in downstream value chains, building on the growing evidence of the limits of downstream CE interventions (e.g. Ekins et al., 2020; IEA, 2024).

Second, the thesis advances understanding of how CE approaches can be applied within the mining sector's upstream activities. Empirically, the mapping of CE approaches in Chile's mining sector reveals ongoing CE implementation in areas such as tailings valorisation, seawater utilisation in ore processing, and equipment remanufacturing. This illustrates tangible pathways for CE implementation in mining, contributing to the literature by showcasing examples beyond the more extensively studied downstream manufacturing and consumer-facing industries.

Third, this research emphasises the fundamental role that the geographical and spatial characteristics of mining regions play in shaping CE transitions. The sector's heavy reliance on geographically fixed resources, combined with the spatial configuration of economic activities in mining territories, leads to specific challenges and opportunities in implementing CE approaches. Enclave economies, dispersed production sites, infrastructure limitations, and weak market linkages distinctly influence the feasibility and effectiveness of circular strategies. By empirically exploring these spatial considerations, the thesis offers a place-based perspective that builds on and expands discussions of geographic and spatial determinants of CE transitions (e.g. Lampinen et al., 2025; Tsui, 2023).

Contributions to economic geography and sustainability transitions literature

The thesis advances economic geography literature by demonstrating how place-specific factors mediate CE transitions in ways that differ from established industrial clusters. The examination of Chile's mining territories reveals distinctive place-based factors, such as the spatial configuration of infrastructure and production networks, and the prevalence of economic enclavism with its associated weak forward and backward linkages, that constrain the application of CE approaches in resource-dependent regions.

This spatial analysis builds upon existing work on the geography of sustainability transitions (e.g. Binz et al., 2020; Bridge et al., 2013; Coenen et al., 2021, 2012) by providing empirical evidence on CE transitions from less-studied extractive regions. The research identifies three key spatial dimensions that impact CE implementation: transportation infrastructure and geographic location of production facilities, regional production networks and market linkages, and value systems and cooperation patterns. These findings align with relational economic geography perspectives on the importance of collaboration and networked interactions (e.g. Bathelt and Glückler, 2003, 2018, 2011; Boschma and Martin, 2007; Yeung, 2005), while showing how weak territorial linkages in mining regions create distinct challenges for CE implementation. These insights also add further empirical evidence to the literature on the territorial impact of CE transitions (e.g. Gura et al., 2023; Lambert et al., 2022; Niang et al., 2023; Veyssière et al., 2022) by showing how the context found in mining regions creates specific barriers to the application of CE approaches.

Complementing this, the thesis contributes to sustainability transitions scholarship by examining how established conceptual ideas from sustainability transition research apply to the extractive contexts and resource-dependent regions in the context of CE transitions. In particular, the findings contribute to debates on niche development, regime transformation,

path dependencies and lock-ins (e.g. Fuenfschilling and Truffer, 2014; Geels, 2002; Geels and Schot, 2007; Smink et al., 2015; Smith et al., 2010) by showing how spatial characteristics create distinct challenges for sustainability transitions and influence the feasibility and success of sustainability transitions.

Finally, this thesis also adds to the evidence base on how spatial contexts mediate transition processes in previously understudied geographic settings. Rather than the diversified industrial regions typically examined in the CE and sustainability transitions literature, this research focuses on regions characterised by resource extraction, economic enclavism, and limited diversification. Therefore, this thesis also contributes to calls for more diverse empirical settings in transitions research (Binz et al., 2020).

7.3. Future research directions

While this thesis provides new insights into the intersection of the circular economy, economic geography and sustainability transitions research, several limitations inhibit the interpretability and generalisability of the findings. Building on the methodological limitations discussed in Section 3.2.3., this section will reflect on some additional limitations of this thesis before pointing out avenues for further research.

7.3.1 Improving data to guide circular economy transitions

One limitation of this research is the lack of available data to investigate the state of and progress of the transition towards a circular economy. Data on resource use, material efficiency, EoL collection and recycling rates, reuse practices and other important circularity indicators remain poorly developed across most sectors and regions. Although this data deficit affects resource-producing regions more heavily as reporting mechanisms for tracking material flows and resource efficiency are often less established than in more industrialised resource-

consuming economies, even in rich, resource-consuming regions, such as Europe and North America, accurate data is difficult to come by.

The absence of accurate, standardised and consistent datasets restricts the capacity of researchers, businesses and policymakers to make evidence-based decisions about CE interventions. To address this problem, future research should focus on developing harmonised reporting frameworks that facilitate the tracking of key circularity indicators, including waste generation, reuse rates, and resource efficiency metrics. In addition, strengthening national, regional, and sectoral reporting would provide a better foundation for strategic planning and academic enquiry.

7.3.2. Applying dynamic probabilistic material flow analysis to other resources

The dynamic probabilistic MFA approach developed in this thesis illustrates the power of combining scenario-building with explicit uncertainty considerations in key parameters. While this approach yielded valuable insights into the limitations of EoL recycling to reduce dependence on primary production, the study was confined to copper. Other minerals critical for the energy transition, such as lithium, nickel, cobalt and rare earth elements, exhibit different demand trajectories, usage patterns, and complexities.

Therefore, applying the dynamic probabilistic MFA methodology proposed in this thesis to other critical energy transition minerals could provide valuable insights into the specific challenges and opportunities for applying CE approaches across different mineral value chains, thereby broadening the evidence base on the role of primary extraction in a circular economy. In addition, integrating the DP-MFA approach with other modelling techniques, such as life-cycle assessment (LCA), could uncover environmental impacts associated with different trajectories. Finally, researchers could add further variables to the DP-

MFA model to investigate the effects of technological innovations, policy interventions, and changing consumption patterns that might influence future material flows.

7.3.3. Broadening the geographical scope of CE research

The case research in this thesis has focused on the Chilean mining industry, generating in-depth insights into one of the world's most prolific copper- and lithium-producing regions. This research design proved beneficial for understanding how a set of institutional, spatial and industrial characteristics converge in a single national and regional context. Nevertheless, many constraints and opportunities faced by other resource-dependent economies with different histories, governance models, infrastructure capacities or social dynamics likely diverge. Consequently, further comparative research is needed to examine how CE transitions might unfold in other geographic contexts.

Future studies could undertake other single case studies or multi-country comparisons, focusing, for instance, on Australia as the arguably most developed and prolific mining jurisdiction, emerging lithium- and copper-producing regions like Argentina with significantly different regulatory approaches to Chile, or regions with lower levels of governance and economic development, such as the Central African copper belt. Such comparative work would help elucidate which practices and frameworks are locally specific and which are transferable. It would also showcase how regions' spatial configuration of economic activities interacts with the unique institutional settings in each jurisdiction. By exploring other geographies, scholars could also more rigorously test the efficacy of policy instruments, strategies or corporate commitments to increase the circularity of upstream extractive activities.

7.3.4. Exploring the influence of spatial factors on CE transitions

This thesis has highlighted the importance of spatial considerations in understanding how circular economy transitions occur in the mining sector and its host regions. As a result, there

is considerable potential to advance our understanding of CE transitions in the context of mining by emphasising how the spatial configuration of economic activities influences the development and application of CE approaches in this context. A larger focus on spatial factors would enable a more nuanced understanding of how circular economy transitions manifest differently across varied geographic contexts. This research direction would also complement emerging research on the geography of sustainability transitions, which calls for a more explicit investigation of the spatial determinants of sustainability transitions (e.g., Binz et al., 2020; Coenen et al., 2021; Hansen and Coenen, 2015), acknowledging that the nature of multi-layered transitions varies widely between locales.

7.3.5. Operationalising CE approaches in the mining sector further

Despite the insights on the dynamics of applying CE approaches in the mining sector that this thesis has presented, there remains considerable scope to deepen scholarly understanding of how CE approaches can be applied and operationalised in the mining sector. As noted in Chapters 5 and 6, research in this domain is still in its infancy, and multiple knowledge gaps persist. While this thesis and other previous studies (e.g. Cisternas et al., 2022; Golev et al., 2020; Kinnunen and Kaksonen, 2019; Lèbre et al., 2017; Tayebi-Khorami et al., 2019; Upadhyay et al., 2021) point to the potential of CE approaches to alleviate some of the sector's adverse social and environmental outcomes, the intricacies of industry-wide implementation and the conditions enabling systemic change warrant further investigation.

First, targeted research is needed to develop more empirical evidence on how CE approaches can be successfully applied to primary extraction activities. As this thesis has demonstrated, the demand for critical energy transition minerals is expected to continue rising for several decades, and evidence suggests that some level of primary mineral production will be required for many decades to come. Hence, investigating how upstream extraction can be transitioned to cleaner modes of production, in addition to increasing our understanding of

downstream application of CE approaches, is of pressing importance. In particular, future scholarship could focus on refining the typologies of CE interventions most relevant to large-scale mining operations, such as waste valorisation, industrial symbiosis with nearby industries, and the enhancement of materials stewardship throughout a mine's life cycle.

Second, although Chapters 5 and 6 have made some inroads into the spatial dimensions of applying CE approaches in the mining sector, more empirical research is required to uncover the complex dynamics of CE transitions in the mining sector and regions hosting mining activities. Future studies that examine how mining firms internalise CE approaches could help clarify the practical challenges and transformation pathways at the organisational level. This could include exploring how knowledge, motivations, and incentives for applying CE approaches vary across different types of companies (e.g. major vs junior mining companies). Similarly, more critical examinations of how entrenched corporate cultures and risk adversity shape the translation of ambitious CE rhetoric into tangible action would deepen the evidence produced in this project.

Third, an additional strand of enquiry could focus on systematically examining the potential to apply CE approaches across all stages of the mining lifecycle. For instance, further research could conduct a life cycle analysis (LCA) to explore how integrating different CE approaches at the mine-site level impacts the environmental footprint of mining operations. For example, comparative life cycle assessments of diverse mine designs could shed light on the relative advantages of specific approaches in mitigating environmental harm and optimising resource use. In addition, more in-depth, technical case studies of real-world examples where mining companies have already integrated CE approaches into their operations would contribute to a better understanding of which practices yield the most significant benefits and under what conditions.

Finally, the environmental justice and socio-political dimensions of applying CE approaches in the mining sector merit greater attention than I was able to give in this confined research project. Local communities frequently bear disproportionate burdens associated with resource extraction, and many future mining operations will be located on land inhabited by Indigenous and First Nation peoples (Lèbre et al., 2020; Owen et al., 2023). Thus, an urgent need is to investigate how incorporating CE approaches into mining operations might change and ideally improve relationships between mining firms and host communities, particularly regarding land use, water rights, and long-term regional development. One potential avenue to uncover these dynamics is ethnographic or participatory research approaches, which could illuminate how the application of CE approaches at large-scale mining operations and in mining regions intersect with local aspirations for more equitable and resilient socio-economic futures.

7.3.6. Studying the CE: a multidisciplinary research domain

Finally, this thesis has attempted to highlight the potential of studying circular economy transitions in the mining sector and resource-dependent regions through a multidisciplinary approach, but much remains to be done to formalise and solidify the conceptualisation of the mining sector's role in a transition towards more circular modes of production and consumption. The intersection of the three scholarly fields that form this study's foundation – circular economy, economic geography, and sustainability transitions research – has a lot to offer to advance insights into the dynamics of circular economy transitions in various geographic and sectoral contexts, and it is up to future research to explore and realise this potential.

To sum up, the diverse set of potential research avenues demonstrates both the complexities and the promise of investigating circular economy transitions in upstream sectors, such as mining. By adopting multi-scalar perspectives that span firm-level analyses, site-specific considerations, and broader sectoral, regional or national studies, scholars can generate

new theoretical insights and practical tools that can shape and guide the transition towards more circular modes of production and consumption in the mining sector and its host regions. Given the mining sector's central role in meeting the raw material needs of the energy transition, advancing a more holistic, empirically grounded understanding of the potential to make mining more circular is more pressing than ever.

7.4. Concluding remarks

This thesis set out to examine whether and how CE approaches can be meaningfully applied to primary mineral extraction. The empirical findings, exemplified by the key energy transition metal copper, give further evidence that while pursuing downstream CE strategies remains essential, the unprecedented material requirements of the energy transition necessitate continued primary mineral extraction for decades. As such, applying CE approaches throughout all segments of the value chain, including mining, is crucial for optimising resource use and minimising environmental harm while meeting the material demands of decarbonisation. As a result, this thesis argued for the need to better understand how upstream value chain segments can be reconfigured to embody circularity principles. Although meeting the raw material demands of the energy transition without compromising environmental and social protections presents complex challenges, the empirical evidence from this study indicates that the CE paradigm offers a promising framework for enhancing mining operations' sustainability.

Using the example of Chile's mining regions, this thesis also demonstrated that the feasibility of applying CE approaches in the mining sector and its host regions hinges on addressing structural barriers, such as economic enclavism, weak market networks, and limited regional diversification, that necessitate coordinated intervention across multiple scales and sectors. Moreover, the research highlighted the importance of taking a place-based approach

that accounts for the unique characteristics and challenges faced by resource-dependent regions, including their institutional frameworks, economic structures, and social dynamics.

Ultimately, this thesis contends that incorporating mining within the CE discourse, rather than treating it as external to it, offers a more realistic and pragmatic pathway towards sustainable resource use. This framing recognises that some level of primary mineral production will remain essential, but argues that embedding mining within CE debates provides opportunities to reduce environmental and social impacts while securing the resources required for the energy transition. Although this thesis makes an initial meaningful contribution to our understanding of how CE approaches can be most effectively applied in the mining sector and its host regions, it will require significantly more research and practical experimentation by both academics and practitioners in order to make a circular mining sector a reality.

8. Co-Authorship Statement

The thesis comprises three empirical research papers that constitute Chapters 4, 5 and 6 of this thesis. The first paper (Chapter 4) was co-authored with Mr Mehmet Metehan Ciftci, a PhD student at the Institute for Sustainable Resources at University College London. I hereby confirm that I have made substantive contributions to the co-authored paper across all stages of research. Each co-author's contribution to the paper was as follows:

Konstantin Born: Conceptualization, Methodology, Software, Investigation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing.

Mehmet Metehan Ciftci: Conceptualization, Investigation, Writing – original draft, Writing – review & editing.

The second (Chapter 5) and third (Chapter 6) papers were sole-authored.

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Supplementary Information

S1. Modelling and calculations

The model works with annualised data and employs a nine-step procedure to calculate its outputs. In addition, it operates in two stages. The first one estimates the stocks and flows of virgin copper extracted in the past. In the second stage, the model estimates the stocks and flows of virgin copper that will be extracted in the future. The following box describes each step in detail (see Box S1.1 for which letter indicates which flow).

Box S1.1

Stage 1 (Historic copper cycle):

Step 1: Virgin production. We use historic copper production data from 1910 onwards to estimate the flow of copper from natural reserves into anthropogenic stock.

1. ***a***[33] = *virgin copper production*

Step 2: Usage allocation. We then allocate the annual copper production to different end product groups in accordance with their usage estimate for the given year based on Glöser et al. (2013). Annual copper production is assumed to be equal to consumption. x denotes the chosen copper-based product category (out of 16). t represents the chosen year (from 1910 up to 2022 until Stage 2/Step 8). Usage allocation is in percentage.

1. $Product\ group\ stock\ creation\ [p_{x_t}] = usage\ allocation\ [u_{x_t}] * a_t$

2. $Product\ group\ stock\ creation\ \ at\ t\ [\boldsymbol{b}] = \sum_{x=1}^{16} p_{x_t}$

Step 3: Primary in-use stock. We then use estimates for the lifetime of each usage category to calculate the time each product group's annual inflow will remain within use. Based on

[33] The letters corresponding to the flows in Figure 4.2 of the main text are in bold.

this, we can calculate the net flows into and out of the stock from primary material. Note that product lifetimes are normally distributed.

1. $Stock\ reaching\ its\ EoL\ [\boldsymbol{c}] = \sum_{x=1}^{16} \frac{p_x}{average\ product\ lifetime_x}$
2. *In-use Stock = stock creation [**b**] (cumulative) – stock reaching its EoL [**c**] (cumulative)*

$$Total\ inuse\ stock\ at\ a\ given\ year\ [p_t] = \sum_{x=1}^{16} \sum_{t'=1910}^{t} (p_{x_{t'}} - \frac{p_x}{average\ product\ lifetime_x})$$

Step 4: End-of-life (EoL) scrap collection. The annual stock that has reached its EoL can then either be collected or it goes uncollected and gets lost to the environment in the form of abandoned products, landfills or into other recycling streams (e.g. steel). We use estimates of the historic EoL collection rate to model past flows of collected end-of-life materials.

1. $\boldsymbol{c}_t = EoL\ stock\ collected\ for\ recycling\ [\boldsymbol{e}_t] + EoL\ stock\ not\ collected\ for\ recycling\ [\boldsymbol{d}_t]$
2. $\boldsymbol{e}_t = \boldsymbol{c}_t * EoL\ collection\ rate\ [\boldsymbol{e}_t/\boldsymbol{c}_t]$

Step 5: End-of-life (EoL) scrap processing. Collected scrap material is then separated before it is processed. However, not all material is processed and significant losses occur during processing. We use estimates of the historic EoL recycling processing efficiency rate to model past flows of collected end-of-life materials.

1. $EoL\ scrap\ recycled\ [\boldsymbol{g}_t] = \boldsymbol{e}_t - Losses\ during\ separation\ and\ processing\ [\boldsymbol{f}_t]$
2. $\boldsymbol{g}_t = \boldsymbol{e}_t * EoL\ recycling\ processing\ efficiency\ rate\ [1 - (\boldsymbol{f}_t/\boldsymbol{e}_t)]$

Step 6: Re-use of recycled material. The recovered material is then recycled again to fabricate new end-use products in the same way described in *Step 2*. We do not account for stocks of recycled material and assume that recycled material will get re-used in the same year in which it has been recycled. This allows us to estimate the share of recycled material that has been used for fabrication and amount of end products produced using recycled materials. r represents the times that the product group has been recycled at t.

1. $Share\ of\ recycled\ material_t = \frac{\boldsymbol{g}_t}{\boldsymbol{a}_t}$

2. $Previously\ recycled\ product\ group\ stock\ creation\ \left[s_{r_{x_t}}\right] = u_{x_t} * \boldsymbol{g}_t$

3. $Creation\ of\ previously\ recycled\ stocks\ (all\ product\ groups)\ [s_r]$

$$= \sum_{x=1}^{16} \sum_{r'=2}^{r} s_{r'_x}$$

Step 7: Total in-use stock. As in step 3 we then use estimates for the lifetime of each usage category to calculate the time each product group's annual inflow will remain within use. Based on this, we can calculate the net flows into and out of the total stock.

1. $Sum\ of\ previously\ recycled\ stocks\ [s_{r_t}] = \sum_{t'=1910}^{t} \sum_{x=1}^{16} \sum_{r'=2}^{r} s_{r'_{x_k}}$

2. $Sum\ of\ previously\ recycled\ stocks\ [s_{r_t}] = \sum_{t'=1910}^{t} \sum_{x=1}^{16} \sum_{r'=2}^{r} s_{r'_{x_k}}$

$$New\ flows = p_t + s_{r_t} - \sum_{t'=1910}^{t} \boldsymbol{c}_{t'}$$

All outflows from the stock enter into step 4 again.

<u>Stage 2 (Future copper cycle):</u>

Step 8: Future primary copper supply. We use the three copper demand forecasts produced by the International Energy Agency (IEA) to derive future primary copper demand.

1. $Future\ primary\ copper\ supply = Future\ copper\ demand - g$

Step 9: Future usage allocation and stock creation. Similar to *Steps 2 and 3*, we then allocate the future primary copper production and future recycled EoL material to different end product groups in accordance with their usage estimate and use lifetime estimates of each usage category to calculate the time each product group's annual inflow will remain

within use. The calculations and formulas are also similar to those used for past primary supply, with the main difference being t denoting here a year between 2023 and 2050.

1. $p_{x_t} = u_{x_t} * \boldsymbol{a}_t$
2. $Future\ product\ group\ stock\ creation\ at\ t\ [\boldsymbol{b}] = \sum_{x=1}^{16} p_{x_t}$
3. *Stocks in use = past stock creation [b] + future stock creation [bf] – past stock reaching its EoL [c] – future stock reaching its EoL [cf]*

Step 10: Future end-of-life (EoL) scrap collection. Similar to *Step 4,* the annual stock that will reach its EoL in the future can then either be collected or it goes uncollected. The future collection rate is determined by adding a linear annual EoL collection growth rate to the latest annual EoL collection rate available (2018) which is held constant until 2022 where the model considers the final year of 'past' collection.

1. *Future EoL collection rate = EoL collection rate (2018) + Annual EoL collection growth rate*

Step 11: Future end-of-life (EoL) scrap processing. Similar to *Step 5,* the collected material in the future can then either be processed or is lost to the environment. The future recycling processing efficiency rate is determined by adding a linear annual EoL recycling processing efficiency growth rate to the latest annual EoL recycling processing efficiency rate available (2018) which is held constant until 2022 where the model considers the final year of 'past' scrap processing.

1. *Future EoL processing efficiency rate = EoL recycling processing efficiency rate (2018) + Annual EoL recycling processing efficiency growth rate*

Step 12: Sensitivity analysis. In the final step we carry out various sensitivity analyses in order to account for the uncertainty of (1) demand and (2) future changes in the collection and recycling of EoL copper. For demand, we use three different copper demand scenarios until 2050 provided by the IEA (2023). To account for uncertainties in future collection and

scrap processing rates, we run 10,000 simulations with normally distributed linear annual collection and recycling processing efficiency growth rates.

S2. Underlying assumptions

S2.1 Stage 1

The model uses a large range of data and underlying assumptions for the instances where (reliable) data was not available in academic and industrial sources. The table below gives an overview of the assumptions that were used:

Table S2.1: Assumptions for stage 1 of the model

Variable	Values used (source)
Historic primary copper production (mining)	1910 – 1959 (Glöser et al., 2013) 1960 – 2020 (ICSG, 2022)
Product groups & usage allocations	To model copper use and in-use stock residence time, we use 16 product groups divided into 5 product sub-categories (building construction, infrastructure, industrial, transport, other-equipment) based on Glöser et al. (2013). 1910 – 1959: 1960 values for product sub-categories[34]. 1960 – 1999: Specific allocation and stock data for each product group (n=16) for this period was not available in the literature. Therefore, we employed the allocation data which was available

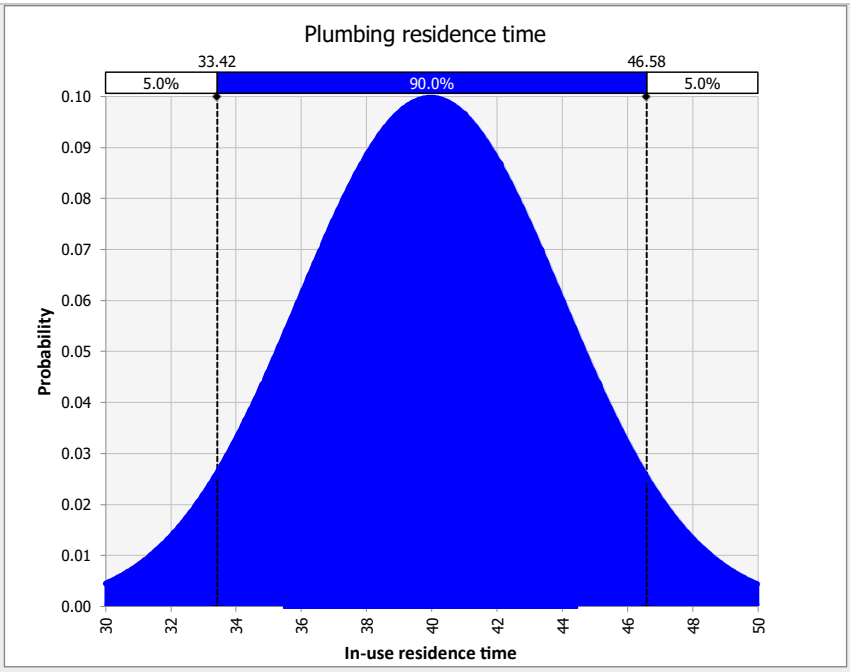
[34] These usage allocations for categories (between 1910-1959) are likely not accurate, but due to the longest average lifetime being 50 years, usage allocation assumptions prior to 1970 do not have any distortion effects on the overall in-use stock.

	for 'sub-categories' (n=5).[35] We used the copper stock data provided by Glöser et al. (2013) for sub-categories. Then, we distributed the sub-category data to the 16 product groups over the period of 1960-1999 using the allocations provided for 2000.[36] 2000 – 2011: Linear interpolation[37] using the data from IWCC (2022) 2012 – 2020: IWCC (2022)
In-use residence times	Average in-use residence times for the 16 product categories are based on Glöser et al. (2013). Values are held constant across the model. The in-use residence times of all products is assumed to be normally distributed around the mean lifetime. We provided an example of the distribution for one product category (plumbing) below:

[35] The product groups (n=16) include plumbing, building plant, architecture, communications, electrical power, telecommunications, power utility, electrical industrial, non elec. industrial, electrical automotive, non elec. automotive, other transport, consumer, cooling, electronic and diverse. The sub-categories (n=5) covering the 16 product groups are building construction, infrastructure, industrial, transport and other (equipment).

[36] This is because after 2000, the gap between aggregate sub-categories (i.e. total of the percentages of product groups for each of 5 sub-categories) based on linearly interpolated estimate of IWCC (2022) data and Glöser et al. (2013) data grows significantly. Moreover, the interpolated IWCC data loses accuracy after 1970s, with some categories dropping below 0%. 2000 is the meeting point of Glöser et al. (2013) and IWCC linear interpolated data for two large categories, i.e. Building & Construction and Other. There is a much narrower gap between Infrastructure, Industrial and Transport product groups. Interpolated IWCC data and Glöser et al. (2013) data for these 3 remaining product groups intersect in 2007, 1990 and 1979. Glöser et al. is the only source providing stock-in-society estimates on a global scale for years before 2000. Hence, we find it sensible to use their data as a benchmark and assume that the estimated product group allocations using IWCC data did not significantly differ before 2000.

[37] Linear interpolation, extrapolation (Ciacci et al., 2017; Henckens, 2021; Schipper et al., 2018) and gradual increase (Blagoeva et al., 2016) are commonly employed to make reasonable estimates to fill the gaps between two known data points in a material supply/demand dataset.

	 *Figure S2.1: In-use residence time distribution for the plumbing product group*
End-of-life collection	Historic EoL collection rates have been drawn from various sources: *2012 – now:* data from annual reports published by the International Copper Studies Group (ICSG). No data was available for 2014 to 2016. Linear interpolation was used to fill the gaps *2000 – 2011:* Glöser et al. (2013) *Prior to 2000:* Steady state rate of 65% based on (Graedel et al., 2011, 2004)
End-of-life recycling processing efficiency	Historic EoL recycling processing efficiency rates have been drawn from various sources: *2012 – now:* data from annual reports published by the International Copper Studies Group (ICSG). No data was available for 2011, 2014 and 2015. Linear interpolation was used to fill the gaps.

	2000 – 2011: Glöser et al. (2013) *Prior to 2000:* Authors' assumption. Linear increase from 50% until 66.58% in 2000 based on Glöser et al. (2013)

S2.2 Stage 2

The second stage of the model estimates the stocks and flows of virgin copper that will be extracted in the future. In order to account for the uncertainties in future copper demand and unknown EoL collection rate and EoL recycling processing efficiency rate growth, the second stage of the model uses probabilistic methods.

For the analysis, we ran 10,000 simulations for each of the three demand scenarios using the software @Risk. Each simulation uses a different combination of EoL collection and EoL recycling processing efficiency growth rates.

Table S2.2: Assumptions for stage 2 of the model

Variable	Values used (source)
Future copper demand	Future copper demand is based on data from the International Energy Agency (IEA) (2023). The IEA has developed three distinct demand scenarios for a range of minerals critical for the energy transition: 1. **Stated Policies Scenario (STEPS)** is the estimated demand for minerals for energy transition under current policy settings based on a sector-by-sector assessment of specific policies that are in place or have been announced by governments. It provides an indication of where today's policies and plans lead the energy sector, and the corresponding demand for minerals.

	2. **Announced Pledges Scenario (APS)** was introduced in 2021 and assumes that all climate commitments made by governments around the world, including Nationally Determined Contributions (NDCs) and longer-term net zero targets, as well as targets for access to electricity and clean cooking, will be met in full and on time. 3. **The Net Zero Emissions by 2050 Scenario (NZE)** is the most ambitious scenario by setting out a pathway for the global energy sector to achieve net zero CO2 emissions by 2050. It does not rely on emissions reductions from outside the energy sector to achieve its goals. Universal access to electricity and clean cooking are achieved by 2030. The IEA provides point-based demand data for all three scenarios for 2025, 2030, 2035, 2040, 2045 and 2050. We connect the different demand data points with a linear function: $f(x) = ax + b$ *a= growth rate between demand data points* *b = demand in t-1* We made a decision to not use the 2025 IEA data point, as we believe that short-term supply constraints make it more prudent to use a uniform growth rate from 2021 to 2030. We then use all subsequent data points (2035, 2040, 2045, 2050).

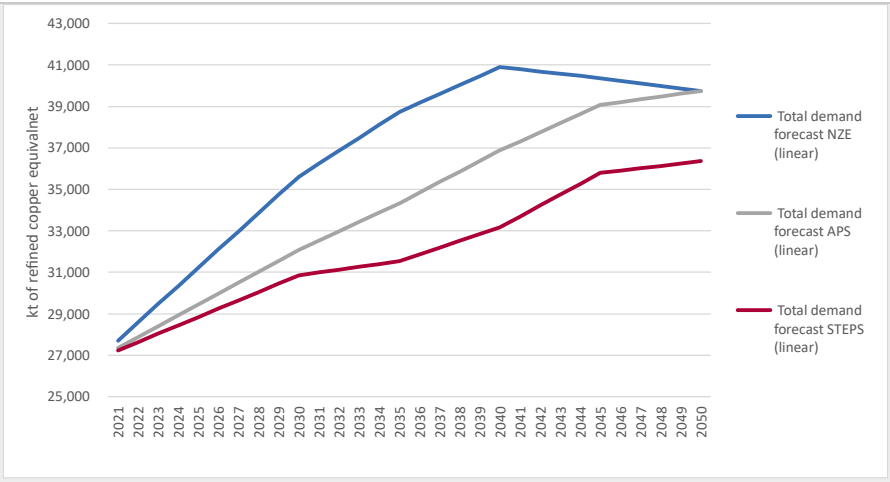


Figure S2.2: Demand pathways under STEPS, APS and NZE demand scenarios

Future end-of-life collection

The future EoL collection rate is assumed to be normally distributed. The chosen distribution looks as follows:

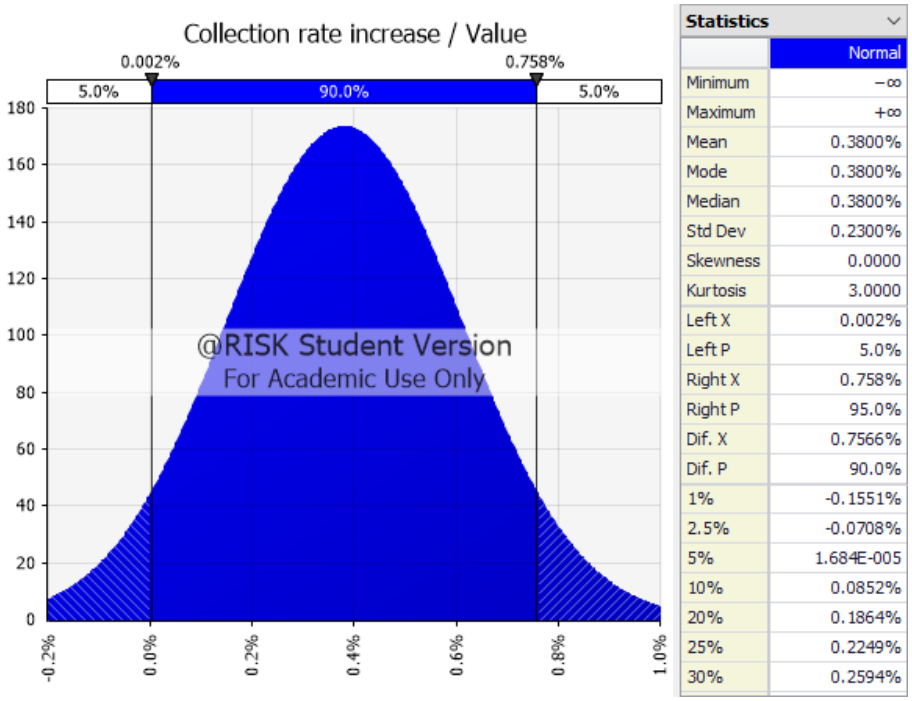


Figure S2.2: Annual EoL collection growth rate distribution

Given the sparse data availability on previous EoL collection rate increases, we chose a normally distributed linear growth rate to simulate the future EoL collection rates. Linear increases are widely used in the literature (e.g. Ciacci et al., 2017; Henckens, 2021; Schipper et al., 2018).

	The boundary conditions of the distribution are based on the literature. We based the 95th percentile boundary on work by Rizos & Righetti (2022) and Abdelbaky et al. (2021), which argue that the maximum achievable copper collection rate for copper in Europe by 2050 is 90%. This would imply a linear 1.21% annual increase in the EoL collection rate in order for the current EoL collection rate of 56% in 2022 to reach 90% in 2050. However, given that EoL copper collection rate in Europe is higher than it is globally (37 % higher) (Ciacci et al., 2017), we reduced the maximum achievable amount globally by the same 37% and therefore assumed a 95th percentile maximum annual increase in the EoL collection rate of 0.76%. Even though it seems unlikely that the EoL collection rate for copper will fall over the coming years given the strong political and strategic pressures to increase collection and recycling rates, we allowed for a 5% chance of a fall in EoL collection rates and therefore set the 5th percentile lower boundary of the annual EoL collection growth rate at 0%.
Future end-of-life recycling processing	The future EoL recycling processing efficiency rate is assumed to be normally distributed. The chosen distribution looks as follows:

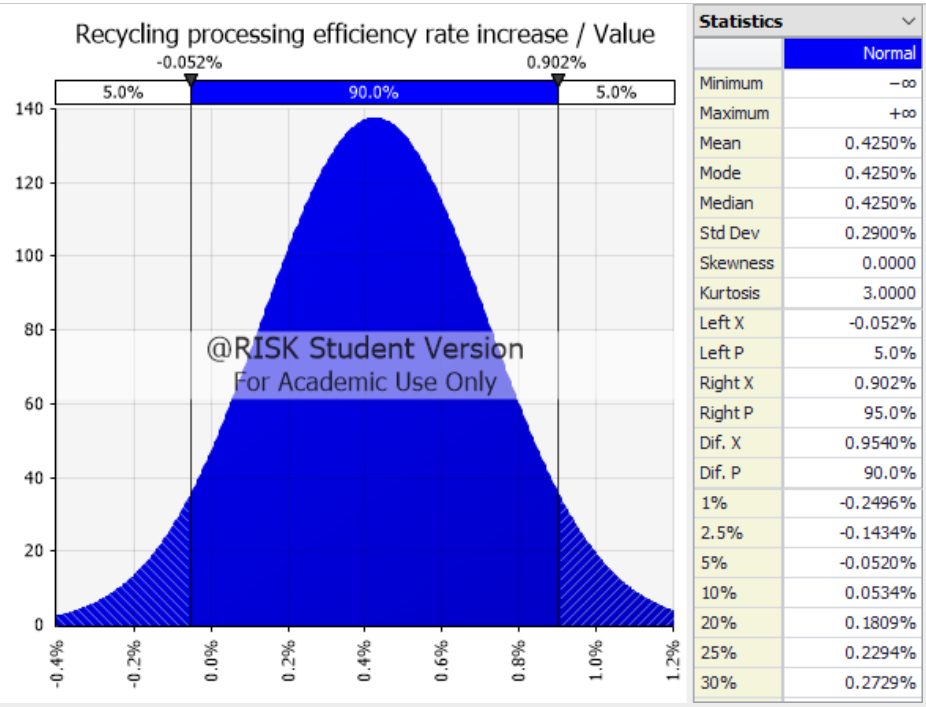


Figure S2.3: Annual EoL recycling processing efficiency growth rate distribution

Given the sparse data availability on previous EoL recycling processing efficiency rate increases, we chose a normally distributed linear growth rate to simulate the future EoL recycling processing efficiency rates. Linear increases are widely used in the literature (e.g. Ciacci et al., 2017; Henckens, 2021; Schipper et al., 2018).

The boundary conditions of the distribution are based on the literature. We based the 95th percentile boundary on work by (Dominish et al., 2019), who argue that the maximum achievable EoL copper recycling processing efficiency rate can be 95% by 2050. They argue that early laboratory results show that 95% recovery is physically possible for clean technology applications. Despite the copper industry's claim that copper is fully recyclable without any loss of function (Copper Alliance, 2022), higher processing efficiency rates seem very difficult to achieve – even under the best conditions - due to inevitable losses in the product lifecycle

	and recycling processes, as well as exponentially increasing energy requirements (Reuter et al., 2013). In order to achieve this maximum rate by 2050, a linear 0.9% annual increase in the EoL recycling processing efficiency rate would be required from the current level of 71% in 2022 in order to reach 95% in 2050. Even though it seems unlikely that the EoL processing efficiency rate for copper will fall over the coming years given the strong political and strategic pressures to increase recycling rates and increasing funding directed towards new recycling technologies, we allowed for a 5% chance of a fall in EoL recycling processing efficiency rate and therefore set the 5th percentile lower boundary of the rate at just below 0%.

S3. Methodological limitations

The model has several methodological limitations:

1. **New scrap.** The model does not account for stocks and flows of new scrap[38], as the vast majority of it is reused immediately in the fabrication process (Glöser et al., 2013). Therefore, new scrap does not act as a demand substitute for primary production and can be ignored for the purpose of this study.
2. **Scrap stocks.** Because there is no reliable data available regarding temporary stocks of old copper scrap, the models assume that the relevant proportion of available scrap that is due to be processed becomes available as secondary material in the same time period.
3. **Product groups & residence times.** The model assumes that product groups and residence time remain constant across all future periods. This is a common approach in other studies as it is difficult to estimate which new copper-intensive products will be

[38] New scrap is the waste that is produced during the fabrication process

introduced into the market in the coming years. In addition, as the average stock residence time in the model is estimated to be 22.85 years today, product group allocation changes over the coming years would only have a limited impact on our results, given the end point of the analysis in 2040.

4. **Economics of copper recycling & copper prices**. The model projections do not explicitly consider the potential impact of changing economics of mineral recycling, such as the impact of higher copper prices on induced innovation (Popp, 1997) or substitution effects.
5. **Future supply dynamics.** The model does not account for potential supply shortfalls and assumes that primary supply of copper matches forecasted demand. Although supply shortages might occur, especially under the highest demand – NZE - scenario, databases that forecast production levels from existing mines and new mine openings are all privately held (e.g. McKinsey MineSpans) and were too expensive for the means of this project.
6. **Specific policy changes to lower demand.** Our scenarios do not directly capture the impact of potential changes in policy or consumer behaviour that could lower overall copper demand through for example significantly higher collection and recycling rates or in-use stock lifetime extensions[39]. However, we do account for lower demand for primary copper material through very high EoL collection and recycling processing efficiency rate growth as part of our probabilistic modelling approach.

[39] See (Simas et al., 2022; Watari et al., 2022) for previous studies that have investigated the impact of specific demand reduction and in-use stock life-time extension policies.

S4. Additional Figures

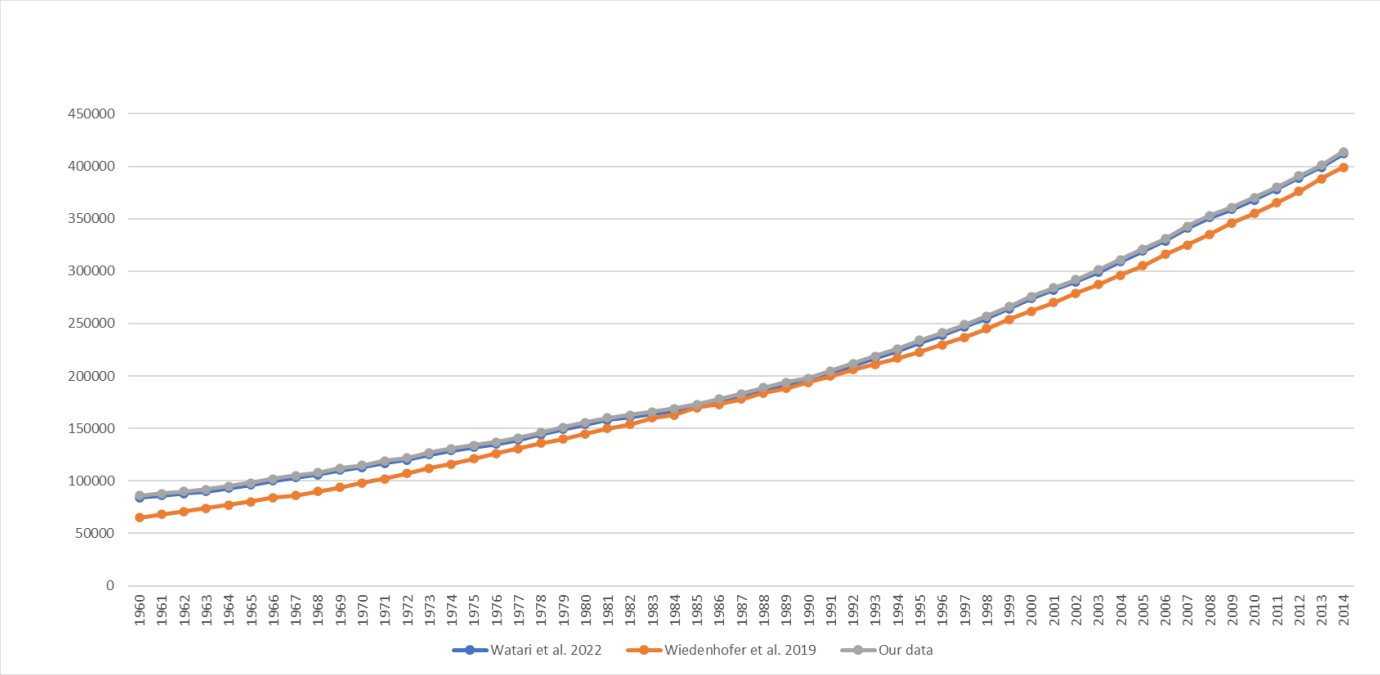


Figure S4.1: Comparison of in-use stock results with other studies (1960 to 2014) (Watari et al., 2022; Wiedenhofer et al., 2019)

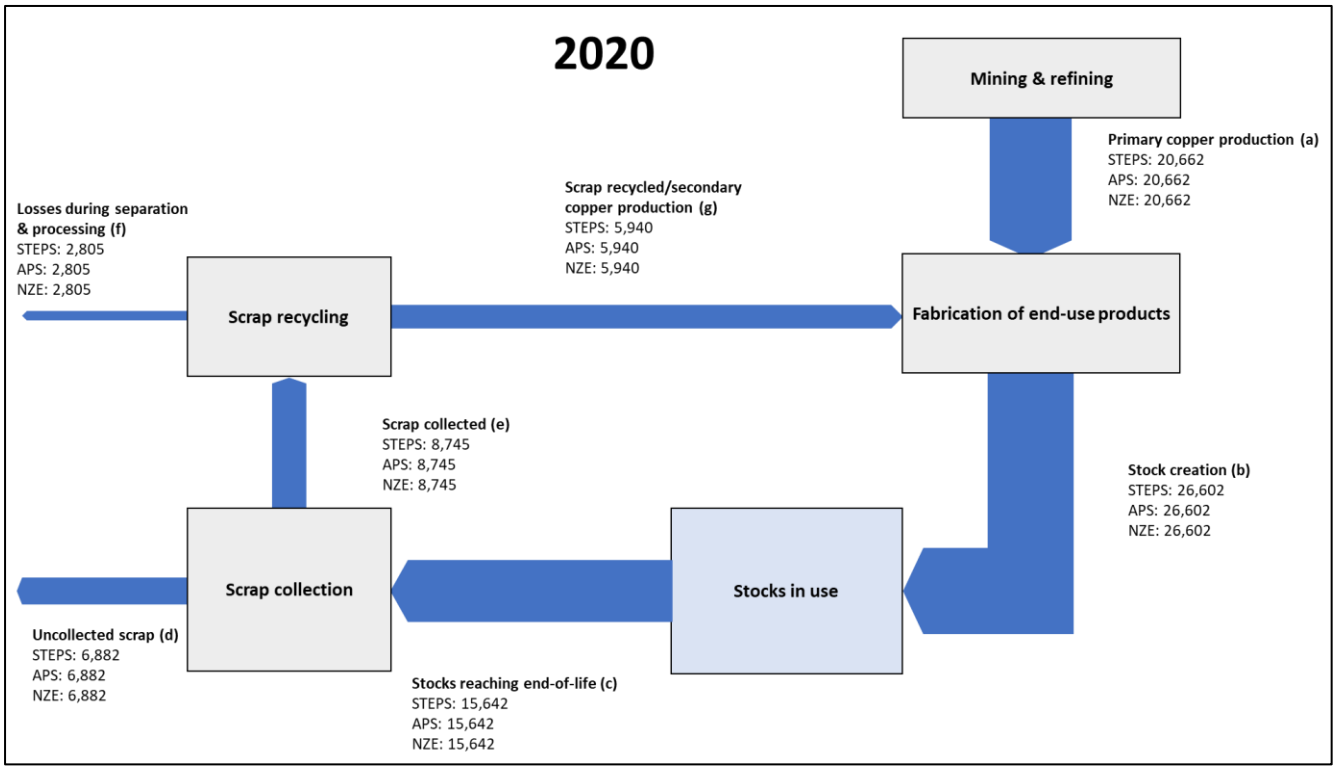


Figure S4.2a: Sankey diagram of copper flows in 2020

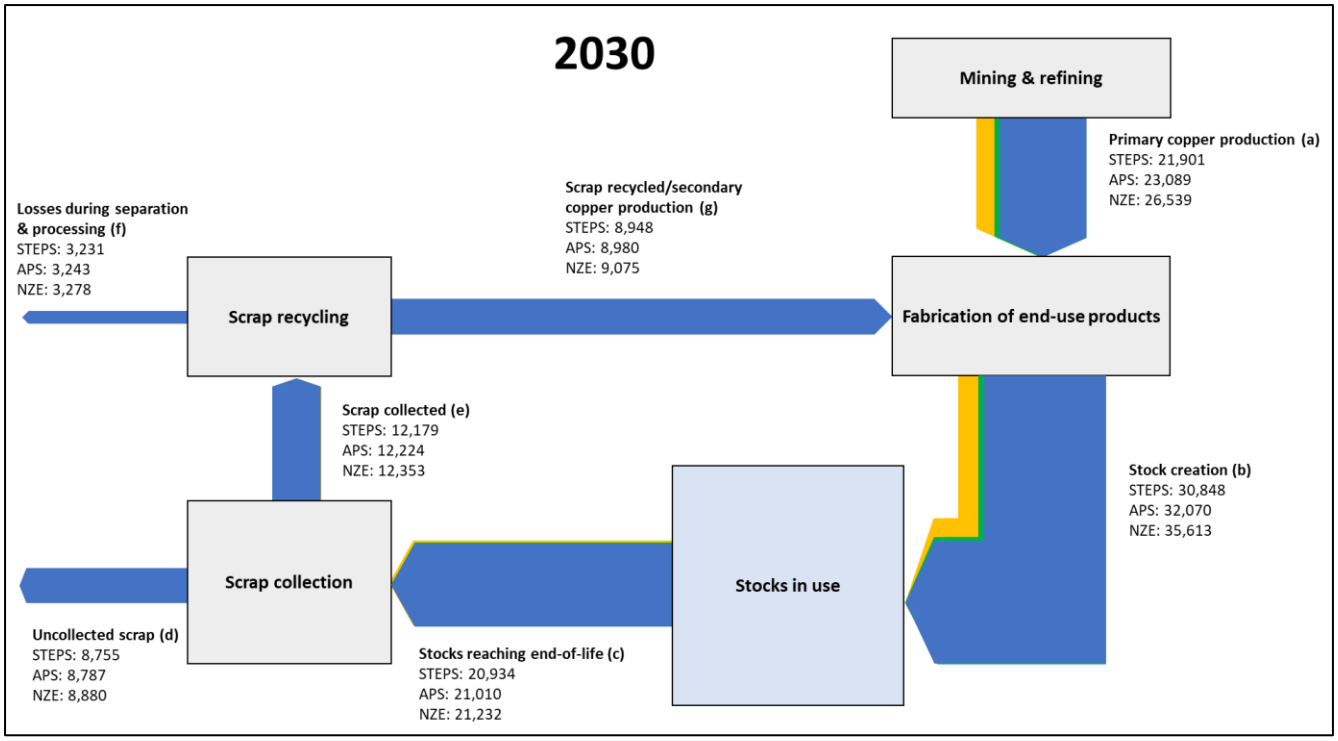


Figure S4.2b: Sankey diagram of copper flows in 2030 (blue = STEPS, green = APS, yellow = NZE)

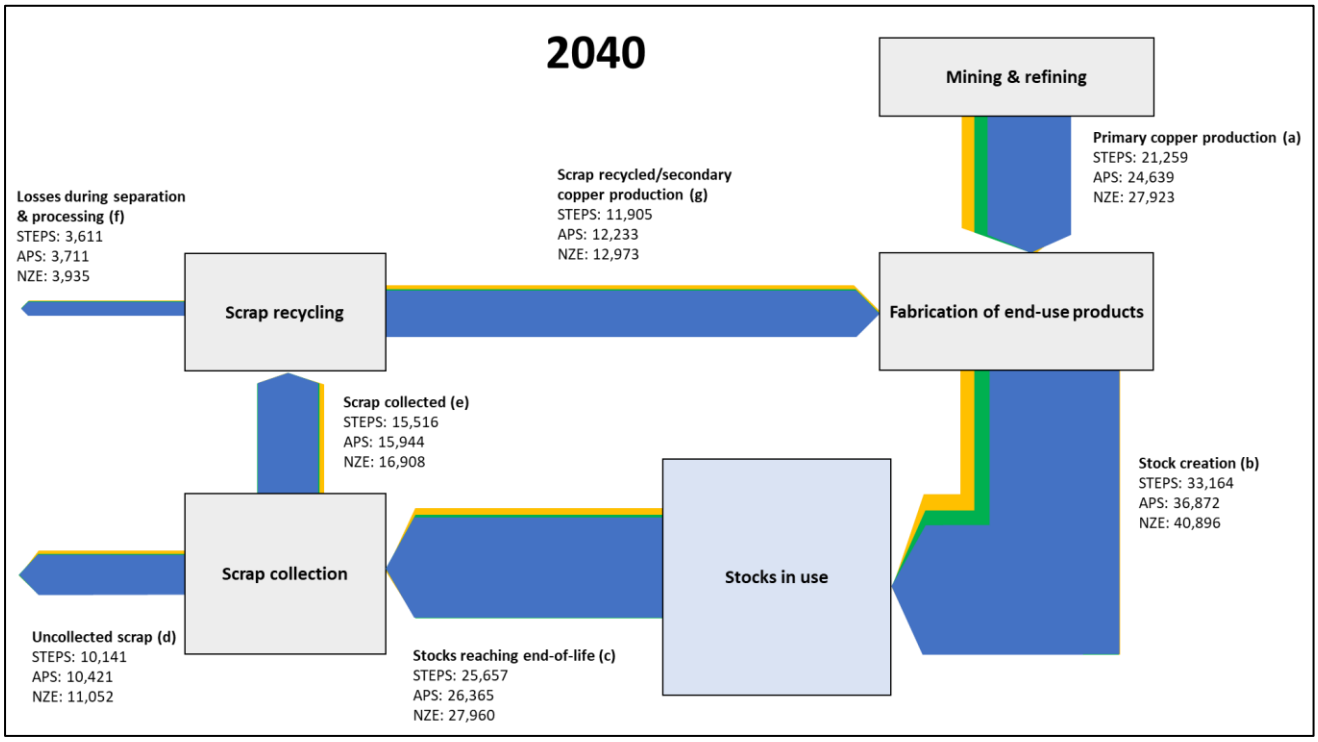


Figure S4.2c: Sankey diagram of copper flows in 2040 (blue = STEPS, green = APS, yellow = NZE)

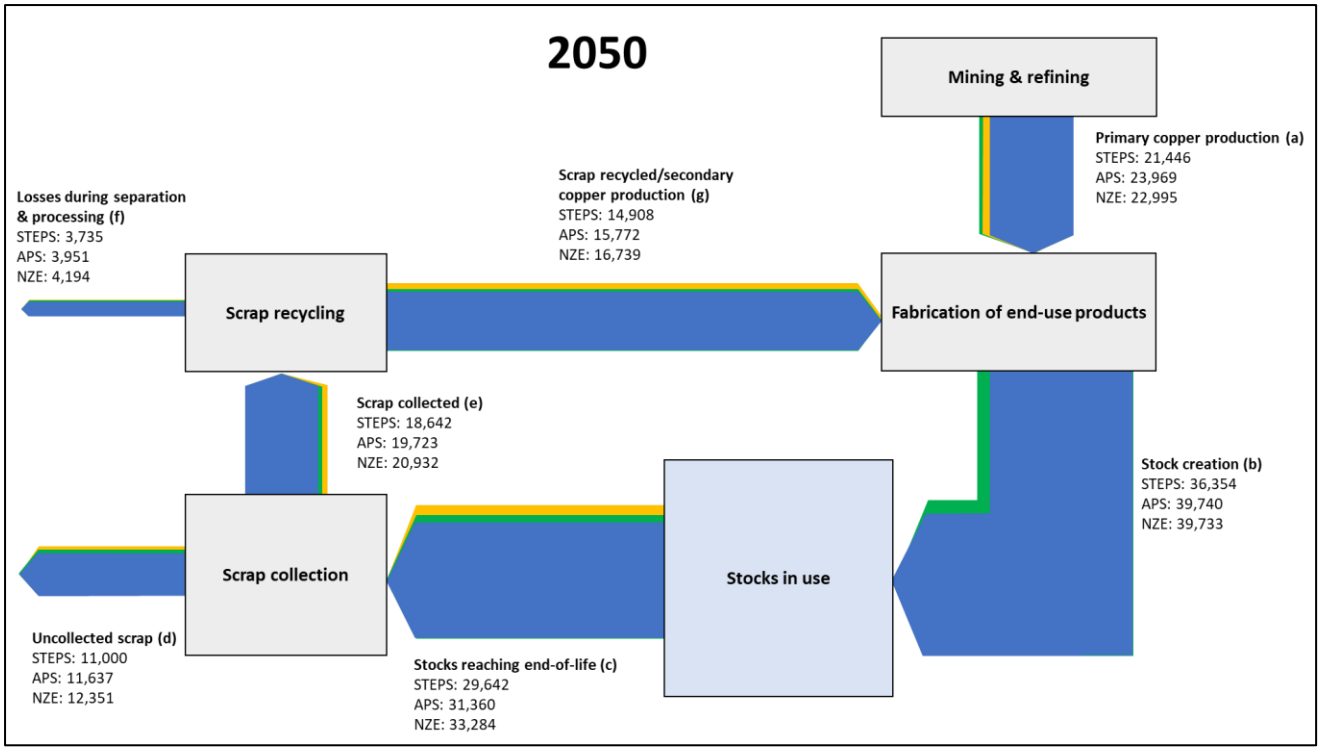


Figure S4.2d: Sankey diagram of copper flows in 2050 (blue = STEPS, green = APS, yellow = NZE)

S5. Guide and Sample Questions for Semi-Structured Interviews

INTERVIEW GUIDE

Interview # _____

Date_____/_____/_____

Start

My name is Konstantin Born and I am an academic at the University of Oxford. First of all, I would like to thank you for participating in this interview.

Introduction to the project

This research explores the mining sector's adoption of circular economy principles and eco-innovation efforts more generally, while also investigating the potential to achieve higher levels of industrial sustainability through the application of nature-based or inspired technologies more specifically. Further, it seeks to create a novel assessment methodology and implementation guidance for the industry to better assess the whole life-cycle costs and benefits of eco-innovation applications. In the first phase of the research project, interviews are being conducted to assess practitioners' knowledge, experiences and views of the adoption of circular economy principles, ongoing eco-innovation efforts, the potential of nature-based and nature-inspired solutions, as well as the wider sustainability priorities in the mining sector.

Interview objectives

The objectives of the interview are three-fold:

1. To get insights into the mining industry's current levels of understanding of circular economy principles and their adoption status.

2. To create an understanding of the current development and adoption of circular economy strategies and practices in the mining industry

3. To measure industry sentiment towards the opportunities offered by circular economy and the perceived barriers to their adoption.

Recording

I would like your permission to tape-record this interview, so I may accurately document the information you give me. If at any time during the interview you wish to discontinue the use of the recorder or the interview itself, please feel free to let me know.

Confidentiality and anonymity

All of your responses are confidential and all the means to remain anonymous will be provided.

The recordings and my notes will be transcribed and analysed by the research team. The analysis will contribute to reports and publications associated to the project. Any specific reference to whatever is said in this interview will be referred to by means of pseudonyms or coded-names.

Voluntary participation and withdrawal

Your participation in this interview is completely voluntary. If at any time you need to stop, take a break, or return to a previous question, let me know. You can decline to respond to any question asked. You may also withdraw your participation at any time without consequence.

Use of the material and formal consent

The interview will form part of the background to our research and could be used in publications for policy and academic audiences, in our newsletters and other communications, as well as for research training and teaching.

We have set out these details on our participant information sheet – do you have any questions about the interview or how we will use the material? Any other concerns?

Are you happy to sign the form as a record of your willingness to participate in our research project? Then with your permission we will begin the interview.

Sample questions for semi-structured interview (~ 60 minutes)

Topic	***Sample Questions***
Sustainability ambitions of the mining industry	What impact has the rise of the ESG debate had on your work?
	Has the rise of the ESG debate changed your company's outlook on sustainability?
	What are the most pressing areas of sustainability that you are currently working on (e.g. water pollution and usage, air pollution, etc)?
Circular Economy Basics	
	How would you define CE in mining?
	How is CE perceived in the mining sector?
	How can CE principles be applied in mining?
	Is the way that CE is commonly understood by companies and governments?
	What is the role of government if the sector is to become more 'circular'?
Sustainability innovation ambitions in the mining sector	Is your company actively innovating around sustainability challenges?
	If yes, how and what are the key target areas? How is the innovation process structured?

	If no, why not? Do you think sustainability innovation is going to become more important?
Circular Economy Implementation	Do you think that CE applications are being looked at more compared to 5 years ago? If yes, why? Why do you think the industry has not been considering CE on the same scale as it is now in the past? If not, why not? How important is the business case or perceived lack thereof for the adoption of CE strategies and practices?
Regulatory environment	How do different regulations in different geographies affect your company's interest in using circular approaches?? If yes, why does a specific regulatory regime affect interest in circularity?