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The Stumbling Block in 'the Race of our Lives': Transition-Critical Materials, Financial Risks and the NGFS Climate Scenarios

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Abstract

Several 'critical' raw materials, including metals, minerals and Rare Earth Elements (REEs), play a central role in the low-carbon transition and are needed to expand the deployment of low-carbon technologies. The reliable and affordable supply of these resources is subject to supply-side risks and demand-induced pressures. This paper empirically estimates the material demand requirements for 'Transition-Critical Materials' (TCMs) implied under two NGFS Climate Scenarios, namely the 'Net Zero by 2050' and 'Delayed Transition' scenarios. We apply material intensity estimates to the underlying assumptions (e.g. with regard to technological innovation) on the deployment of low-carbon technologies to determine the implied material demand between 2021 and 2040 for nine TCMs. We find several materials to be subject to significant demand-induced pressures under both scenarios. Subsequently, the paper examines the possible emergence of material bottlenecks for three materials, namely copper, lithium and nickel. The results indicate possible substantial mismatches between supply (accounting for variables such as existing reserves, technological deployment and recycling rates) and demand, which would be further exacerbated if the transition is delayed rather than realised immediately. We discuss these findings in the context of different possible transmission channels through which these bottlenecks could affect financial and price stability, and propose avenues for future research.

Keywords: Low-Carbon Transition, Commodities, Critical Raw Materials, Scenario Analysis, Financial Risk, Price Stability, Geopolitics of the Energy Transition

JEL classification: Q02, Q5, Q42, L72, G10, E44, E31, F5

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NON-TECHNICAL SUMMARY

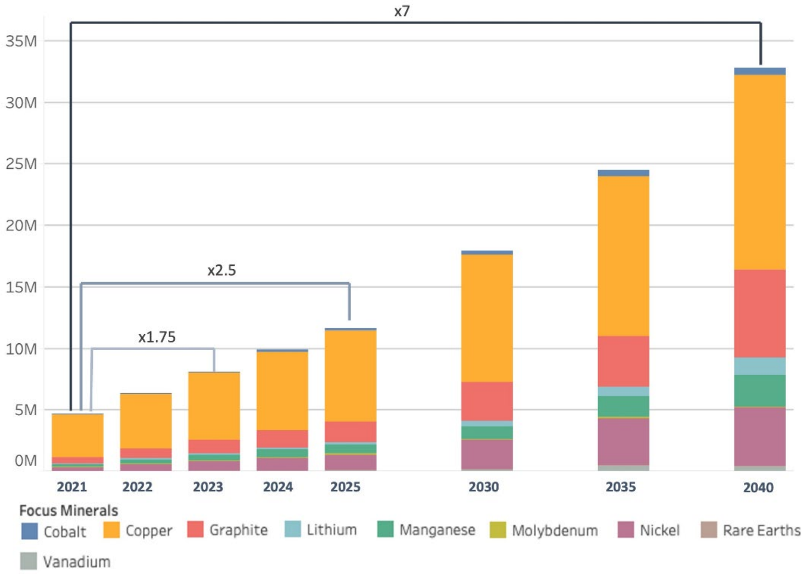
Limiting global warming to well-below 2°C requires a fast-paced, large-scale economic transition to a net-zero economy. If the climate transition is 'the race of our lives', then transition-critical materials (TCMs) could be the stumbling block. Indeed, the necessary scaling-up of relevant technologies, including solar panels, batteries for electric vehicles (EVs) and supportive grid infrastructure, will cause significant demand for, and dependency on, a variety of materials such as copper, lithium, nickel and cobalt. These materials are set, mutatis mutandi to rival the role formerly played by fossil fuels. Recent research identifies that material bottlenecks could stem from TCMs supply-demand imbalances, which could then have consequential impacts in delaying the transition.

Against this backdrop, this paper offers three contributions. First, building on previous studies and on several databases, we develop a methodology to identify the criticality of materials in the context of the low-carbon transition. The identification of TCMs is based on an assessment of several demand-induced pressures and supply-side risks, including reserves and extraction geographical concentration, country risk profile and water stress. Nine TCMs are then selected for further assessment to explore the demand-related pressures arising from the climate transition.

Second, based on the data collected (including technological assumptions from sources such as the International Energy Agency), the paper investigates the demand for TCMs implied by the Climate Scenarios of the Network for Greening the Financial System (NGFS). Under the 'Net Zero by 2050' scenario, absolute annual demand for all focus materials increases from 4.7 million tonnes (Mt) in 2021 to 32.8Mt in 2040 (see figure 1). Under the 'Delayed Transition' scenario, total demand increases from 1.7Mt to 42.9Mt including EVs, and from 0.94Mt to 32.1Mt excluding EVs, between 2021 and 2040. Based on the findings, three materials (lithium, copper and nickel) are further investigated in the context of supply development projections to identify potential bottlenecks.

Third, the paper suggests some avenues for future research to better understand how TCMs could have macroeconomic and financial implications. Further firm- and sector-level assessments (accounting for factors such as price volatility, geopolitical tensions and national strategies aimed at strengthening strategic autonomy) will be needed to better understand how global value chains may become reorganised because of TCMs, and how such reorganisation could impact different countries' trade balances.

Figure 1. Demand for TCMs (in Mt) implied by the NGFS 'Net Zero by 2050' scenario



Note: The demand for TCMs induced by the NGFS 'Net Zero by 2050' Scenario increases from 4.7Mt in 2021 to 32.8Mt in 2040. Total demand is multiplied by 2.5 between 2021 and 2025, and by 7 between 2021 and 2040. The demand for copper largely drives this trend, followed by other TCMs such as graphite, nickel and lithium.

Matériaux critiques pour la transition, risques financiers et scénarios climatiques du NGFS

RÉSUMÉ

Plusieurs matières premières « critiques » jouent un rôle central dans le déploiement de technologies essentielles à la transition vers une économie bas-carbone. L'approvisionnement fiable et abordable de ces ressources est soumis à des risques du côté de l'offre, face à une demande appelée à croître de manière constante dans les prochaines décennies. Cet article estime de manière empirique les besoins en « matériaux critiques pour la transition » (MCT) induits par deux scénarios climatiques du NGFS, à savoir le scénario « Net Zero d'ici 2050 » et le scénario « Transition retardée ». Sur la base des hypothèses retenues (notamment en ce qui concerne l'évolution de différentes technologies), nous trouvons que plusieurs MCT pourraient être soumis à des pressions importantes induites par la demande dans les deux scénarios analysés. Les déséquilibres potentiels entre offre (induite par des facteurs tels que les réserves existantes ou le taux de recyclage de différents MCT) et demande seraient exacerbés dans le scénario où la transition serait retardée. L'article examine également la potentielle émergence de goulets d'étranglement pour trois MCT, à savoir le cuivre, le lithium et le nickel. Enfin, nous discutons de la manière dont ces résultats pourraient donner lieu à de futures recherches visant à comprendre comment des problèmes d'approvisionnement en MCT pourraient affecter la stabilité financière et des prix.

Mots-clés : transition bas-carbone, matières premières critiques, analyse de scénarios, risques financiers, stabilité des prix, géopolitique de la transition énergétique

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1. Introduction

Limiting global warming to well-below 2°C requires a fast-paced, large-scale economic transition to a net-zero economy. Jeremy Grantham refers to the climate transition as the 'race of our lives'[1]. If the climate transition is a race, then transition-critical materials (TCMs) could be the stumbling block. This block has the potential to derail the transition and commit the global economy to exacerbate physical risks from climate change. The deployment of low-carbon technologies plays the central role in enabling the transition to be realised. The necessary scaling-up of relevant technologies, including solar panels and supportive grid infrastructure, will cause significant demand for, and dependency on, a variety of materials, including copper, lithium, nickel, cobalt and rare earth elements (REEs). These materials are set to rival the role formerly played by fossil fuels. They are often identified and formally labelled by governments as 'critical raw materials' or 'critical minerals' for their vital inputs into national strategic industries and due to import dependencies (European Commission, 2010; 2020a; USGS, 2022a). However, the criticality of TCMs depends on their necessity to enable the climate transition, rather than the economic importance or import dependency to any single economy. Demand for these materials is set to significantly increase in the coming years in the face of supply-side constraints and potential risks.

In this context, recent research identifies materials that are critical to enabling the climate transition, exploring economic and financial risks associated with material bottlenecks stemming from supply-demand imbalances, and the consequential impact in delaying the transition (e.g. Gielen, 2021; IEA, 2021a).

This paper builds on the well-established research on critical minerals and the emerging literature on their role in the transition to offer three contributions on 'transition-critical materials' (TCMs). First, building on previous studies and on several databases, we develop a methodology to identify the criticality of materials in the context of the climate transition. The identification of TCMs is based on an assessment of the demand-induced pressures and supply-side risks. Nine TCMs are then selected for further assessment to explore the demand-related pressures arising from the climate transition.

Second, based on the data collected, the paper investigates the demand for TCMs implied by the Climate Scenarios of the Network for Greening the Financial System (NGFS) (NGFS, 2022). These scenarios are increasingly used by central banks, supervisors and market participants to assess financial risks (Bank of England, 2022; ECB, 2022; Moody's Analytics, 2022; S&P Global, 2022a). The corresponding scenario narratives detail the deployment of energy generation, electrical storage, electric transportation and supportive grid infrastructure, all of

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[1] Jeremy Grantham, CBE, co-founder of asset management firm, GMO, and founder of the Grantham Research Institute on Climate Change and the Environment at the London School of Economics, referred to the climate transition as 'the race of our lives'. https://www.gmo.com/globalassets/articles/white-paper/2018/jg_morningstar_race-of-our-lives_8-18.pdf

which are heavily dependent on minerals and the related supply chains. We estimate the implied future demand for nine TCMs between 2021 and 2040 under the 'Net Zero by 2050' and 'Delayed Transition' NGFS Climate Scenarios. The paper focuses on both, the relative rate of production increase, as well as the absolute increases in annual production. Based on the findings, three materials (lithium, copper and nickel) are further investigated in the context of supply development projections to identify potential bottlenecks. The purpose is to offer insight into the differing material requirements under the two scenarios, and an initial discussion into the subsequent price and macro-financial stability implications. This exploratory exercise provides first insights on demand estimates and the possible implications in the context of constrained supply.

Third, as central banks and financial supervisors are primarily concerned with safeguarding financial and price stability, the paper highlights that the implications of TCMs for their core mandates clearly require further research. Here, the paper extends the demand-side analysis to discuss the potential financial risks stemming from the realisation of the transition. In this context, the paper is the first to argue that the rapidly growing topic of material bottlenecks should be understood within the context of central banks' mandates of not only price, but also financial stability. The proposed approach also offers a starting point for future research to assess financial risk transmission channels stemming from TCMs, considering the high concentration of supply chains, and increasing future demand for transition-enabling technologies.

The analysis presented here supports the findings of previous research that highlight the links between supply-demand imbalances in transition enabling-materials, specifically given the inelastic supply in the short-run and the possible emergence of material bottlenecks, and risks for the climate transition (Gielen, 2021; IEA, 2021a). However, our analysis extends beyond this to argue that the related consequences may be a source of macroeconomic instability, specifically price and financial volatility. Importantly, the creation of short-term market tensions is likely to be surmounted by the physical consequences of not achieving a Paris-aligned transition. Different transition narratives, considering both the climate policy target and transition pathway trajectory, equate to significantly differing material demand projections.

The paper is structured as follows. Section 2 provides an overview of the existing literature on critical and conflict minerals in the context of the climate transition. Section 3 discusses the major factors and risks shaping the demand for, and supply of, TCMs. The central empirical contribution of the paper in section 4 first focuses on establishing a relative risk ranking for TCMs' exposure to demand-induced pressures and supply-side risks. Second, the section provides estimates for the demand for a selection of nine materials under the 'Net Zero by 2050' and 'Delayed Transition' scenarios. Third, it compares the demand estimates for lithium, nickel and copper with supply projections to identify and discuss possible bottlenecks. Section 5 explores the potential transmission mechanisms from supply-demand imbalances through the real economy to financial risks, highlighting the potential price and financial stability implications. Section 6 summarises and highlights areas of future research.

2. Literature review

The reliable supply of materials has already been subject to attention by governments, academics and other stakeholders prior to the context of the climate transition. The identification of 'critical raw materials' or 'critical minerals'[2], and 'conflict minerals' has typically focused on the supply-side risks, cutting across a variety of issues, including domestic conflicts, economically strategic sectors, and the global political economy. Many of these themes are subsequently relevant for transition-enabling materials in light of the climate transition.

Fundamentally, 'critical raw materials' or 'critical minerals' are identified as such due to their role in strategically important economic sectors and related import dependence (Nassar & Fortier, 2021). Based on this, governments have compiled lists to identify materials that are critical for their economy (European Commission, 2010; 2020b; 2020c; USGS, 2022a), thereby also highlighting their exposure to a range of political and economic risks (Committee on Earth Resources, 2008). For example, Coulomb et al. (2015) identify a list of 12 to 20 critical minerals based on the identifications of supply risk factors and economic importance for OECD countries. Their assessment criteria include political and economic stability of producing countries, substitutability of minerals and the production share by country. For national governments, military, information and communication technologies, and strategic industries have traditionally been the leading factors in these assessments. Geopolitical considerations have typically dominated the research on the topic due to its salient presence in supply risks. In this context, the production of semiconductors has received considerable attention due to geopolitical factors associated with the supply chain (Teer & Bertolini, 2022). However, no single list-defining criteria for 'critical' minerals or raw materials exist, with criteria and context substantially differing by country.

The related concept of 'conflict minerals' focuses on how exploitation and trade contribute to or benefit from violations in human rights, international humanitarian law, or crimes under international law (Global Witness, 2014). For example, the mining of 'conflict minerals' in the Democratic Republic of Congo (DRC), specifically cobalt, has often been connected to human right abuses, including child labour, as well as weak overall governance (Church & Crawford, 2018; Prause, 2020; Mazalto, 2009; Nuklu et al., 2018). This is particularly prolific in cases of artisan and small-scale mining (ASM), which constitutes approximately 20 per cent of the DRC's exports of cobalt (Nuklu et al., 2018). These operations are typically associated with

[2] These materials are either labelled as "critical minerals" or "critical raw materials" by governments; the underlying concepts are similar, thus the terms are often used interchangeably.

higher death and injury rates compared with their large-scale counterparts (Church & Crawford, 2018). Lithium mining in Zimbabwe, and copper and gold mining in Indonesia have been discussed in a similar context (Maguwu, 2017; Jensen & Asmarini, 2015). Conflict minerals are therefore also subject to special supply risks, linking them to the climate transition (Church & Crawford, 2020).

However, more recently, the criticality of minerals has been increasingly discussed with a focus on the climate transition. The technologies required to enable a low-carbon transition are greater in material-intensity compared with their carbon-intensive counterparts (IEA, 2021a). Consequently, supply-side risks are also relevant in the context of materials that enable the transition through the deployment of low-carbon technologies. Most materials are abundant in necessary quantities to achieve a transition; however, not necessarily in concentrations that makes extraction at current prices economically viable. There are several antecedent conditions that determine the supply of most materials to be inelastic in the short-term, specifically, the long lead development times of opening new mines and establishing refining capacity, which in turn is heavily influenced by geographic location, ore grade and financing conditions (World Bank, 2016). These development processes can exceed a decade for some materials (World Bank, 2016; Schodde, 2017). These constraints that may cause short-term supply inelasticity can amplify the impact of risk materialisation within material supply chains.

In this context, two primary types of supply-side risks factor can be identified, namely geopolitical dynamics and production-related risks, which include social impacts, operational issues and environmental-related risks. The geopolitical dimension relates to dependence on the global value chains to supply sufficient materials for, among other strategic economic applications, the production of transition technologies. This dependence is a source of significant vulnerability and risk for import-dependent economies, exacerbated by a reliance on supply chains that are subject to high geographic and market concentration (Gielen, 2021). Production-related supply-side risk relates to the significant negative environmental impact resulting from the extraction, processing and manufacturing of many materials (Elshkaki et al., 2017). The negative environmental impact puts the scaling up of supply to meet increasing demand at odds with stricter environmental regulation and broader socioenvironmental and socioeconomic factors. Furthermore, as the impacts of climate change increase in their potency, in particular flooding and water stress, environmental-related events pose an increasing source of supply risk (Northey et al., 2017).

The paper also provides an assessment of the supply risks in relation to the low-carbon transition. Elshkaki et al. (2013) find, based on a dynamic material flow model for the base metals (aluminium, copper, chromium, nickel, lead and iron), that supply does not limit the introduction of renewable electricity generation technologies, while highlighting that constraints in the supply of several materials may limit the deployment of photovoltaic (PV) solar technologies. De Koning (2018) investigates potential bottlenecks in the supply of a wide range of metals, assuming the gradual introduction of far-reaching climate policies leading to full global implementation by 2050.

Compared with previous literature that focuses on materials in the context of conflict or national security, the climate perspective incorporates an additional component of risk, namely demand-induced risk. Various studies estimate the potential material demand under different transition scenarios, highlighting the potential implications and material bottlenecks that may arise from different transition pathways (Deetman et al., 2018; Hund et al., 2020; IEA, 2021a; Watari et al., 2019). Not all studies find demand-induced pressures to be an issue for bottlenecks, Gruber et al. (2011) find lithium supply not to be an expected bottleneck for the rapid adoption of electric vehicles. However, this is possibly due to the long-time horizon adopted in the paper (2010-2100), therefore failing to account for sudden, near-term influxes in demand.

Numerous studies estimate future material demand under different transition scenarios, including those by the IEA (IEA, 2021a), the World Bank (Hund et al., 2020), as well as the SET-Plan scenarios developed by the European Union (Moss et al., 2013a; European Commission, 2022a). With varying scopes, some focus only on electrical generation technologies (Elshkaki et al., 2013; Moss et al., 2013b), electric vehicles (EVs) (Ballinger et al., 2019; Fishman et al., 2018), specific materials, such as transition-related platinum bottlenecks (Rasmussen et al., 2019), or REEs in wind energy in Colombia (Gallego, 2021)(Gallego, 2021). While some studies include a range of technologies (Månberger & Stenqvist, 2018; Blagoeva et al., 2016), only a few of them conduct a comprehensive assessment with all currently known technologies and sub-technologies relevant for the transition, with the exception of the recent World Bank (Hund et al., 2020) and IEA reports (IEA, 2021a). Importantly, the different approaches also highlight the trade-off between a broader inclusion of technologies and the need for greater assumptions on innovation, development and substitution.
(Gallego, 2021)
In a seminal contribution, the IEA (2021a) investigates the role of critical minerals in the 'clean energy transition'. The study estimates various demand and supply constraints and the projected increased demand under different IEA scenarios, namely the stated policy scenarios (STEPS) and sustainable development scenario (SDS). The World Bank (Hund et al., 2020) focuses instead on different IEA transition scenarios, namely the 'Beyond 2-Degrees', '2-Degrees' and 'Reference Technology' scenarios. Deetman (2018) offers a comprehensive analysis by also including household appliances and relies on an Integrated Assessment Model (IAM) to assess global resource and metal demand to investigate how demographics and climate policies can lead to a large increase in metal demand. Moreau et al. (2019) suggest, based on a comparison of differing metal requirements under different transition scenarios, that scarcity relates more to techno-economic supply than raw material availability,

highlighting the importance of considering both, the rate of demand increases and the availability of substitutions.

While the supply and demand of materials in the context of the climate transition is extensively explored in the literature, the subsequent link to prices and financial risks is underdeveloped. Building on this comprehensive literature, initial further research has also identified the potential economic implications from the materialisation of bottlenecks. Boer et al. (2021) identify metal-specific demand shocks and estimate supply elasticities to assess the price impact of the low-carbon transition in a structural scenario analysis exercise. Moreover, following the geopolitical tensions between China and Japan in 2011 and the subsequent impact on the prices of REEs, Baldi et al. (2014) find a negative relationship between the price of dysprosium and neodymium, and the stock market performance of clean energy indices. Conversely, the link between oil price shocks and financial performance has been extensively explored in the past (Le & Chang, 2015; Demirer et al., 2020; Sadorsky, 1999).

As discussed in the literature, the disparity between climate ambition and material availability, and therefore between demand and supply, can lead to bottlenecks that threaten the realisation of a Paris-aligned transition (Hund et al., 2020; IEA, 2021a). As a central contribution of this paper, we start to explore how the risks of bottlenecks could have potential macroeconomic stability implications by, for example, causing price volatility, as discussed by (Boer et al., 2021). However, only materials that are directly relevant for low-carbon technologies and the climate transition are within the scope of this paper. In this context, we aim to provide supporting evidence of the possibility of material bottlenecks and contribute analysis on the possible subsequent financial risks.

3. Supply-demand (im)balances and Transition-Critical Materials risks

For this paper, we define 'Transition-Critical Materials' (TCMs) as the materials that will have to serve as critical, and therefore transition-enabling inputs, for the low-carbon technologies needed to bring about the energy transition. While there is a strong overlap reflected in the common language between the literature on 'critical minerals' and 'conflict minerals', and the literature that specifically examines materials needed for the climate transition, it is important to note that while many of the materials and risks between the topics are shared, they ought to be distinguished.

This is the case because, first, the criticality of TCMs is determined by us on the basis of the global need for low-carbon technologies, and not based on the strategic economic importance of a given mineral for any single economy, which is the underlying criteria for the traditional classification of 'critical minerals'. Subsequently, there are discrepancies between the lists of relevant materials for each context. For example, while our list of TCMs includes copper, which is imperative for global grid infrastructure, as well as almost all low-carbon technologies, copper is often excluded from national 'critical raw material' lists due to its well-diversified supply, located in 'low-risk' countries.

Second, the context of the climate transition offers an additional dimension, which may interact and exacerbate the supply-side risks and demand-induced pressures. Therefore, to examine materials in this new context, new terminology can be helpful to make these distinctions, leading us to propose 'transition-critical materials' (TCMs) as a term and concept to establish this alternative perspective to assess material supply and demand risks specifically in the context of the climate transition.

In our initial identification of TCMs, we identify 27 materials (Table 1) that are substantially important for transition technologies, including renewable energy, electrical storage, electric vehicles and grid infrastructure. Our selection of these transition-enabling materials is collated from a variety of previous studies that specifically focus on materials required for low-carbon technologies (see Appendix 1 for the literature review of material requirements). The list of TCMs includes a variety of minerals and elements, of which the five included Rare Earth Elements (REEs) (praseodymium, neodymium, terbium, dysprosium and yttrium) are a special subgroup. This list of TCMs strongly overlaps with the commonly defined groups of 'critical minerals' and 'critical raw materials', highlighting that demand for these materials also originates outside of their use in low-carbon technologies for the climate transition.

Table 1. List of identified 'transition-critical materials' (TCMs)

Aluminium	Lead	Silicon
Cadmium	Lithium	Silver
Chromium	Magnesium	Tantalum
Cobalt	Manganese	Tellurium
Copper	Molybdenum	Tin
Gallium	Neodymium	Titanium
Graphite	Nickel	Tungsten
Hafnium	Niobium	Vanadium
Indium	Rare Earth Elements	Zinc

Source: Compiled by authors.

The supply and demand of these identified TCMs are subject to considerable uncertainty and risks, related to the structural factors for production, geopolitical and production-related risks, and uncertainties over the future developments of demand. Abrupt increases in the annual demand for these materials, coupled with inelastic supply in the near-term, may lead to material bottlenecks and sharp price increases, as well as delay the low-carbon transition. These supply and demand factors may have interactive qualities, which can lead to an exacerbation of 'situational scarcity' and prolong the impact on low-carbon technological deployment. Building on the analysis outlined in detail in Section 4, Table 2 highlights the demand for several key TCMs (as well as coal and natural gas for comparison) required for low-carbon technologies. There is significant overlap in the list for TCMs and more typically defined 'critical raw materials'. This reflects the broad demand for most TCMs from across different economic sectors and technologies. For many of these, aside from the transition, demand will further increase in coming decades from other economic sectors, including the digitalisation of our economies and security concerns. This section identifies the key factors of supply and demand, which determine the potential materialisation of bottlenecks, and the subsequent possible price and financial risks.

Table 2: The relative demand of each selected material for different technology types

	Cobalt	Copper	Graphite	Lithium	Manganese	Molybdenum	Nickel	Rare Earths	Vanadium
Solar PV		high							
Wind		high			medium	medium	medium	medium	
Concentrated Solar		high			high		medium		
Geothermal		low			high	high	high		
Hydro		medium			medium	medium	low		
Biomass	low	high					low		
Nuclear		high			medium	low	medium	low	low
CCS	low	medium			high	low	high		medium
Coal	medium	low			low	low	medium		
Natural Gas	low	low					low		
Electric Vehicles	medium	high	high	high	medium		medium	medium	
Energy Storage	low	high	high	high	medium		medium		high

Source: Compiled by authors (*= low, = medium, = high).* The selection of materials is based on the analysis of supply and demand risk factors conducted in Section 4 (Table 5) and a thorough literature review of technology material intensity requirements (see Appendix 1).

3.1 Demand-induced pressures for Transition-Critical Materials (TCMs)

The demand-induced pressures for TCMs are contingent upon two factors. First, technological innovation and material substitutability; and second, the climate transition pathway, both in terms of climate ambition and transition trajectory. Neither of these components are fixed or determinable, resulting in substantial uncertainty in determining future estimates of TCMs demand.

Furthermore, the quantities of materials required vary significantly across the spectrum of known technologies and within sub-technologies. For example, different designs of solar panels require different sets of materials, including copper, silver and thin films of tellurium, indium and gallium (Carrara et al., 2020). The ramifications for these demand uncertainties are material-specific, and dependent on the cross-cutting use of specific materials across technologies, the substitution of technologies and the transition demand relative to historic production (Hund et al., 2020). Technological innovation that advances substitutability and contributes to efficiency improvements can significantly change demand for, and thereby dependency on, specific TCMs, with advancing technological innovation contributing to uncertainty over how demand for a given material will develop in the future (World Bank Group, 2017) (World Bank Group, 2017).

Firms have a strong incentive to advance technical innovation to substitute and diversify, thereby reducing dependencies in light of shortages and higher prices (McKinsey, 2022; IEA, 2021a). For example, cobalt-free batteries for short-range EVs (IEA, 2021a) and REE-free wind turbines (Barteková, 2016) are understood to have also been developed to reduce specific TCM dependencies. Furthermore, environmental and reputational concerns can also incentivise substitution and reduce demand. For example, EV manufacturers have switched to more nickel-rich cathodes in recent years to reduce dependency on cobalt due to supply chain-related concerns (Noerchim et al., 2021). However, alternatives are not always readily available for most crucial applications and substitution options are often not as efficient or effective. For example, aluminium is an alternative for copper in electricity transmission, but its conductivity is only 60% the rate of copper and does not have the same thermal characteristics (IEA, 2021a). Hence, there are limitations to the extent to which substitution and innovation can offset increased material costs fuelled by increased demand.

As highlighted in this paper, the level of climate ambition and the trajectory of the transition pathway greatly determine material demand at different points in time of a given transition pathway. With low-carbon technology, and therefore material demand dependent on supportive climate policies, technological innovation and consumer or investor sentiment, the magnitude of demand growth significantly depends on the realised transition pathway. Different transition pathways are associated with significantly different implications for required quantities and timing of material demand (IEA, 2021a; Hund et al., 2020). Consequently, it is difficult to accurately determine future demand for TCMs stemming from the climate transition. This is the especially the case given the potential relationship between the rate of increases in material demand and the level of innovation or substitution, which, as discussed below, is likely transmitted through prices.

3.2 Supply-side risks for Transition-Critical Materials (TCMs)

Supply-side risks, and their subsequent potency, are determined by supply-side shocks and material-specific vulnerabilities. Supply-side shocks, which are realised in the form of reduced supply and subsequent situational scarcity transmitted through higher prices, are primarily constituted of geopolitical and production-related risks. Production-related risks include operational issues, social opposition and impacts, and environmental risks, particularly water stress. While most TCMs remain relatively well supplied, significant price increases and volatility of some materials (e.g., lithium) in the context of strong experienced or expected future growth or supply chain disruptions add to supply uncertainties (S&P Global, 2022b).

Geopolitical factors are a main source of supply-side shocks due to strong dependence on imports. This provides exporting governments with a powerful tool of economic statecraft, as shown by the response to a geopolitical incident between Japan and China in 2011, specifically highlighting the risks of import dependencies (Kalantzakos, 2018). Governments, including in the US, the EU and Canada, have begun to recognise the dependency of their climate neutrality transition on the secure supply of TCMs (European Commission, 2020b; USGS, 2021; Government of Canada, 2021).

Geopolitical relations may determine the availability, access to, and supply of TCMs and thereby the ability to scale up low-carbon technologies. Unforeseen geopolitical events present considerable non-linear supply risks, with a substantial impact on prices. For example, following the invasion of Ukraine, the London Metal Exchange (LME) had to suspend trading after a sudden 250% price spike, which exposed a major manufacturer to a possible credit default (Burton et al., 2022). In this context, the main channel for mitigating geopolitical risks would be an increase of domestic supply. In practice, this is constrained by the allocation of material deposits, and is often economically, socially and environmentally a non-viable solution. Innovation in mining and processing technology could nevertheless influence geographical dominance by either mitigating or strengthening the geopolitical dominance of major supplying countries (comparable to how the hydrofracking revolution turned import-dependent countries, such as the US, into producing nations (O'Sullivan et al., 2017)).

A secondary source of supply-side risks are production-related risks. These include the negative environmental considerations, operational issues, and governance of mining and refining operations (Michaels et al., 2022). These risks can be differentiated into physical and transition risks, stemming from dependency and impacts, similar to those identified by the emerging literature on nature-related financial risks (NGFS-INSPIRE, 2022).

Transition risks for mining operations originate from the impacts on biodiversity, but also on local communities and workers. Due to material extraction often taking place in biodiversity hotspots, increased mining and processing can be connected to deforestation, increased pollution and environmental catastrophes (Sonter et al., 2018). Regulatory, socioeconomic and socioenvironmental objections have already been a consideration in closing rare earth mines (e.g., in the US, France and China) (Pitron, 2020). Social factors, such as labour strikes, are frequently cited in mining companies' financial reports as a reason for halted or reduced production (BHP, 2020; Anglo American, 2019). Hence, the possible materialisation of environmental physical and social risks may lead to greater regulatory requirements, and the possible closure of mining projects.

Physical risks emerge from the dependency of mining operations, particularly on water availability (ENCORE, 2022). Climate change is expected to cause more frequent droughts and alter water flows. Physical weather events, partially caused by climate change, frequently affect mining projects, reducing production (Anglo American, 2020; BHP, 2020), and this impact is likely to continue to increase as climate change-induced water stress becomes more prevalent (WRI, 2022). These physical impacts can also worsen the environmental impact as flooding can lead to spills of hazardous waste from mine sites or waste storage, and tailings dam failure, with extensive environmental damage (Rüttinger et al., 2020). Ensuring resilience of mining operations can add to costs, while failing to do so poses a threat to reliable supply. The temporary closure of current mining projects due to environmental and social events exacerbates the volatility in production, while the objections against new mining activities prevents the mitigation of supply risks. At an aggregate level, these production-related risks may reduce overall supply and worsen situation scarcity.

Supply-side vulnerabilities determine the exposure of material-specific supply chains to supply-side shocks, as well as the likelihood and impact of their materialisation in the form of supply elasticities. Supply vulnerability is determined by three main factors, namely geographic and market supply concentration, mine project development lead times, and the recycling rates of different materials. Geographic and market concentration determines the exposure of material-specific supply chains to supply-side shocks, as well as the likelihood of their materialisation, whilst the subsequent two factors largely determine the short-term elasticity of supply, and partially dictate the economic or price impact of supply-side risk materialisation. These factors determine the supply elasticity for TCMs and constitutes their vulnerability to shocks originating from supply-side risks.

Geographic concentration is determined by the locations of economically viable deposits, mine extraction and refining capacity. Market concentration is shaped by the capital-intensive nature of establishing mining projects (S&P Global, 2022b). The supply chains of many TCMs are highly concentrated, often with over 60% of production located only in a few countries (see Table 5). Different countries may dominate different parts of the supply chain for individual materials. For instance, lithium mine extraction is dominated by Australia (52.3%), which produced twice the output produced by Chile in second place, despite the fact that most of the economically viable reserves are located in Chile (43.8%) (USGS, 2022b). It is important to note that geographic concentration dynamics and the exposure to supply-side risks is subject to the political and economic stability of the country, with more fragile states constituting higher risk.

Mine development from deposit discovery to first production is subject to long project lead times. Consequently, supply is relatively inelastic in the short-run, which contributes to the risk of supply-demand imbalances. New mine development can take decades, with the global average over the 2010-19 period standing at 16.5 years for new production operations (IEA, 2021a), with tier 1[3] discoveries becoming less frequent (Schodde, 2019). Furthermore, there is a significant degree of variability in mine development times depending on material, location and mine type (World Bank, 2016). Declining ore grade for some materials is closely linked to the development lead times of mines, which, along with higher costs of material extraction and increasing capital costs, has emerged as a supply-constraining factor (IEA, 2021a; Schodde, 2017). For example, global copper production is understood to be potentially close to the peak due to declining ore quality and economic reserve exhaustion (Northey et al., 2017; Schodde, 2014). Lower quality ores lead to a lower conversion rate between discovery and development, indicating that future production will be more capital-intensive and extend mine development times.

Secondary supply, namely from scrap and recycled material, is a potential source that could contribute to reducing supply-side vulnerabilities. However, recycling rates for most TCMs are currently low (Månberger & Stenqvist, 2018; UNEP, 2011). The historically low prices of most materials have contributed to disincentivising and even hindering the financial viability of the technological advancement of recycling. This has especially been the case for REEs, where recycling rates are currently as low as 1 percent (Tsamis, 2015). Furthermore, the existence of specific engineering barriers (e.g., highly flammable lithium-ion batteries electrolytes, or the high-quality grade of metals required for EV cathodes) is preventing a rapid increase in recycling (Harper et al., 2019; Olivetti et al., 2017). The availability of secondary supply through recycling is also limited by the availability of suitable material and suitability of recycled material for applications (Upadhyay et al., 2021). The former is dependent on the lifespan of end-use sectors and historic production volumes, limiting recycled supply in the near-term in face of increasing demand. Overall, these supply elasticity-determining factors increase the TCMs' vulnerability to shocks originating from supply-side risks.

Supply-side shocks, and the significant vulnerability of TCMs to them, pose a threat to the reliability and expandability of TCM supply. The economic and price impact of their materialisation will be highly dependent of the material-specific vulnerabilities. Furthermore, the likelihood of their materialisation is also partially dependent on the demand-induced pressures for each material. In this regard, there is considerable uncertainty around both the demand and supply-side factors, which determine the price of these commodities and the subsequent deployment of low-carbon technologies. However, most of these materials are subject to significant demand-induced pressures and supply-side risks, which may lead to material bottlenecks over the course of the transition.

[3] Tier 1 discoveries are 'company-making' mines and are large, long life and low cost with NPV (Schodde R. , Trends in exploration, 2019)

4. Methodology for the criticality assessment and material demand estimation

Our analysis of TCMs, and the related supply and demand risks, is conducted in three steps based on the comprehensive methodology outlined in this section. The developed approach is used to, first, assess the criticality of individual material with the aim of identifying those with the greatest risk exposure profile in the context of the low-carbon transition. In a second step, the methodology enables us to estimate the implied demand for TCMs under the 'Net Zero by 2050' and 'Delayed Transition' scenarios between 2021 and 2040 for nine materials, considering relative and absolute demand increases. Finally, we assess the annual demand increases against the projected supply of lithium, nickel and copper to highlight the materiality of demand-induced risks, the possibility of material bottlenecks and the related potential financial risks (see Appendix 4 for detailed account of modelling choices and related list of assumptions).

4.1 The methodology for the criticality assessment

Building on the initial identification of 27 TCMs (Table 1), we further refine the assessment with the aim of identifying the nine materials most exposed to demand-induced risk from the transition for the following two parts of our analysis. This further refinement of the list of TCMs also serves to establish a relative risk ranking between different materials. Due to the unique supply and demand risk profile of each material needed for low-carbon technologies, it is necessary to conduct a material-specific risk assessment. The assessment highlights which materials are most exposed to bottlenecks caused by a sudden increase in the rate of deployment of low-carbon technologies while facing inelastic supply. The assessment of criticality considers both, supply and demand, and includes the factors that determine the vulnerability of supply, supply-side risks and demand-induced pressures discussed in Section 3. More specifically, it includes seven supply and three demand-related factors, offering a comprehensive assessment of the critical role of materials in the low-carbon transition, namely the TCMs[4]. Social and environment-related, as well as geopolitical supply risks, are incorporated indirectly through the S&P Global country risk indicators (S&P Global, 2022b), which include political, operational, social and terrorist risks, and therefore enable us to capture the location-specific dynamics associated with geographic concentration.

The first three supply-chain indicators (reserve concentration, extraction concentration and refinement concentration) are a summation of the percentage of global supply held in the top three countries for each stage of production. Country and water stress risk are calculated by multiplying the regional indicators (taken from S&P Global and WRI) with the countries' reserve and extraction concentration, respectively, weighted by percentage of global supply.

[4] The indicators include, on the supply side, (1) reserve concentration, (2) extraction concentration, (3) refining concentration, (4) investment risk profile, (5) water stress risk, (6) lead development times and (7) recycling rates, and on the demand side, (1) transition demand risk, (2) cross-cutting risk and (3) substitutability risk. Full list of indicators in Appendix 1.

$$\left(CountryRisk_{x_1} * \ CountryRes._{x_1}\right) + \cdots + \left(CountryRisk_{x_3} * \ CountryRes._{x_3}\right) \quad (1)$$

$$\left(WaterRisk_{x_1} * \ CountryExt._{x_1}\right) + \cdots + \left(WaterRisk_{x_3} * \ CountryExt._{x_3}\right) \quad (2)$$

Where, $\boldsymbol{CountryRisk}$ = country risk taken from S&P Global, $\boldsymbol{CountryRes.}$ = country share of economically viable reserves, $\boldsymbol{WaterRisk}$ = water stress taken from WRI, $\boldsymbol{CountryExt.}$= country share of global extraction, $\boldsymbol{x}$ = country,

Lead development times and recycling rates are taken from various sources, including (Månberger & Stenqvist, 2018; UNEP, 2011; Schodde, 2019; Schodde, 2014; IEA, 2021a). Transition demand risk is calculated by material demand increase from low-carbon technological deployment in 2030 indexed to 2020 demand under the NGFS 'Net Zero by 2050' scenario. Cross-cutting risk refers to the number of technologies that rely on each specific material (taken from literature review in Appendix 1). Finally, substitutability risk is a qualitative assessment conducted by authors based on the literature review and wider research.

4.2 Estimating Implied Demand for Transition-Critical Materials (TCMs) under the NGFS Scenarios

Building on the 'Net Zero by 2050' and 'Delayed Transition' scenarios[5] (NGFS, 2022), we explore the implied TCM demand between 2021 and 2040. The MESSAGEix-GLOBIOM1.1 sub-variation integrated assessment model is chosen for our analysis (see Appendix 4 for further details). Our approach considers material-intensity estimates for each technology and sub-technology. These estimates are then applied to the annual capacity additions for each technology, accounting for differing technology market shares over time.

Energy Generation and Storage

In a similar approach to IEA (2021a), Watari (2019) and McLellan (2016), we rely on the material intensity estimates for each type and sub-type of low-carbon technology provided in the literature, using tonnes per gigawatt (t/GW) (see Appendix 1). Where different material intensity estimations are available in the literature, we give preference to those in more recent publications. Where possible, our estimations are aligned with those of the IEA (2021a), which are informed by private communications as well as the public literature. We then apply the material intensity estimations to the annual capacity additions for technology and sub-technology outputs for both energy generation and energy storage. Within our calculations, we convert the energy storage power density estimates provided by the MESSAGE model into energy density estimates by assuming a discharge rate. The lifespan of

[5] The NGFS portal contains six scenarios – Net Zero by 2050, Divergent Net Zero, Below 2°C, Delayed, Nationally Determined Contributions (NDCs), and Current Policies. The scenarios are outlined in three sub-variations, provided by different Integrated Assessment Models (IAMs), namely GCAMS, REMIND-MAgPIE, and MESSAGE.

energy generation and storage technologies are already accounted within the NGFS scenarios.

Battery Chemistry, EVs, and Freight Calculations

Assumptions relating to battery chemistry are taken from the Argonne National Laboratory's (ANL) BatPaC Model Software (ANL, 2022). The ANL software includes a breakdown of materials required for a selection of different lithium-ion batteries and are provided in active material percentages by weight (Ibid). From these values, we use the atomic mass units (AMU) of the different elements to calculate the composite ratio and individual ratio for each element within the different battery chemistries. The kilogram (kg) per watt-hour (Wh) is derived per type of battery chemistry from the BatPaC Model Software. In a second step, the individual metal ratios are multiplied by the kg per Wh. The same calculation is used to calculate the weight of lithium required for the liquid lithium-ion electrolyte. The weight per material is multiplied to give the intensity in the form of t/GWh. These calculations are then aligned with the estimates provided by the IEA (2021a) within their analysis. The calculation is as follows:

$$CR = (AMU_{E_1} . ER_{E_1}) + \cdots + (AMU_{E_x} . ER_{E_x}) \quad (3)$$

$$W_{E_x} = \left(\frac{AM_W}{CR}\right) . \left(\frac{AMU_{E_x}}{ER_{E_x}}\right) \quad (4)$$

Where, $\boldsymbol{CR}$ = battery composite ratio, $\boldsymbol{AMU}$ = atomic mass unit, $\boldsymbol{ER}$ = element ratio, $\boldsymbol{E_x}$ = with respect to element, $\boldsymbol{W}$= weight, $\boldsymbol{AM}$= active materials

Once the battery chemistries are derived, we apply these to the projected battery capacity deployed for EVs and freight road transportation. Supplementing the IAMs used in the NGFS scenarios, the projection of future uptake of EVs by the EV Data Centre does not account for different transition scenarios, and therefore limits our analysis on the impact of material demand from EVs under the two scenarios. However, the EV Data Centre offers a breakdown based on battery capacity deployed and is also used within the IEA (2021a) calculations for material intensity. We then calculate the material demand by multiplying the relevant material intensity (t/GWh) with the projected annual deployment in battery capacity for EVs (GWh).

While the NGFS scenarios do not project the number of freight vehicles under the different scenarios, they include the final energy usage from freight road transport. Following the methodology proposed by Watari (2019), we estimate the number of freight vehicles associated with the respective energy demand based on several assumptions. Starting from the energy used by electric freight vehicles per kilometre, the average kilometres driven per year, the average battery size of an electric freight vehicle and the lifespan of the battery (Earl et al., 2018), and following the methodology by Watari (2019), we derive the number of freight vehicles using the following calculation:

$$FV_E = (E_D . D_t) \quad (5)$$

$$FV_n = \left(\frac{FT_E}{FV_E}\right) \quad (6)$$

Where, $\boldsymbol{FV_E}$ = energy-use per freight vehicle, $\boldsymbol{E_D}$= energy-use per km, $\boldsymbol{D_t}$= average distance per year, $\boldsymbol{FV_n}$ = number of freight vehicles, $\boldsymbol{FT_E}$ = total freight energy-use

Network Grid Calculations

Increased electrification of energy supply will require greater transmission networks to transmit and distribute the energy. Therefore, estimates of the implied copper demand from the deployment of network lines significantly add to the overall analysis. Following the methodology by Deetman et al. (2021), and taking averages from various sources (Global Transmission, 2022; Eurelectric, 2013; Seneca Group, 2014; Arderne et al., 2020), we estimate current grid lengths. Once the current high voltage (HV) lines are estimated, we use a region-specific fixed ratio to determine the current medium- and low-voltage (MV & LV) lines, relying on the same sources. The future grid growth is determined using a growth factor for HV lines based on indexed growth of installed generation capacity, again following (Deetman et al., 2021) and using the following calculation:

$$HVGrid_{reg,yr} = HVGrid_{reg,2019} * \frac{GenCap_{reg,yr}}{GenCap_{reg,2019}} \quad (7)$$

Based on the total estimated line length, transformers and substations are estimated in fixed ratios based on units per km and following the approach by Harrison et al. (2010) and Turconi et al. (2014). The ratio of overhead to underground lines for each type of voltage line (HV, MV, LV) is taken from (Eurelectric, 2013) and applied globally. The material intensity for voltage-specific lines, including transformers and substations, is calculated as follows:

$$GridMat_{reg,yr,volt} = \left(Grid_{reg,yr,volt} * Line_{type}\right) * MI_{lines} + Grid_{reg,yr,volt} * \frac{Units_{trns.\ \&\, sbst.}}{km} * MI_{trns.\ \&\, sbst.} \quad (8)$$

Where, $\boldsymbol{HVGrid_{reg,yr}}$ = high-voltage grid, considering region and year expressed in km, $\boldsymbol{GenCap_{reg,yr}}$= energy capacity, considering region and year expressed in gigawatts, $\boldsymbol{GridMat_{reg,yr,volt}}$= material requirement for a grid network, considering region, year, and voltage line expressed in t/GW, $\boldsymbol{Line_{type}}$ = refers to whether the grid line is overhead or underground, $\boldsymbol{MI_{lines}}$ = material intensity of voltage lines, $\boldsymbol{\frac{Units_{trns.\ \&\, sbst.}}{km}}$ = the number of transformers and substations, per kilometre.

The regional breakdown from the MESSAGEix-GLOBIOM1.1 model is used to account for regional differences in grid length (NGFS, 2022). The regional figures provided by Deetman et al. (2021) are integrated into the NGFS model regional categories, requiring regional data to be aggregated to correspond with the regional definitions in the NGFS model. Where regional data is not available, global averages are used to ascertain grid length against generation capacity.

NGFS Model Alterations, Sub-technology Market Share, and Material Intensity Improvements

The overall analysis focuses on material demand over a period of 20 years between 2021 and 2040. Due to the 5-year step averages provided by the NGFS Scenario IAMs, our ability to assess the potential year-on-year impact of material demand from low-carbon technology deployment is limited. To overcome this limitation, we interpolate between years assuming a linear trajectory in capacity addition increases within a 5-year time-period, focusing thereby on technologies and the overall time-span where the difference between 5-year periods is significant. While this may slightly distort the outputs of the NGFS model, it enables us to examine the change in material demand over a year-on-year timeframe. The rationale for the linear trajectory assumption is to reflect a more gradual over time adoption of technologies and to offer a more detailed illustration of demand-induced pressures on material supply.

For the investigated 20-year time frame, there are two key factors that will affect the material demand related to innovation and technological development, namely (i) the market share of sub-technologies and (ii) the improvements in material intensity per GW/GWh. Within specific technologies, sub-technological differences and changes can have a material effect on materials required (e.g., the mineral requirements of Direct Drive Wind Turbines in comparison to Gearbox Wind Turbine Configurations (European Commission, 2020b)). To account for the expected dynamically changing market shares of different sub-technologies over time, we use the sub-technology market shares provided by the IEA (2021a). Building on the provided 10-year intervals between 2020 and 2040, we calculate the market share change on a linear basis between periods and apply the market shares to the relevant sub-technologies. Furthermore, increased efficiency from innovation and technological development will likely lead to reduced material demand per GW/GWh. Following the IEA (2021a), we assume a 10% material intensity reduction over the entire period, in a linear trajectory, to account for efficiency improvements.

$$TMR_e = \left(\left(CA_{T_1} \,.\, MI_{e_1}\right) .\, MS_{ST_1}\right) + \cdots + \left(\left(CA_{T_x} \,.\, MI_{e_x}\right) .\, MS_{ST_x}\right) \qquad (9)$$

Where, $\boldsymbol{TMR_e}$ = total material requirement per material, $\boldsymbol{CA_{T_x}}$ = capacity addition per technology, $\boldsymbol{MI_{e_x}}$ = material intensity per material, $\boldsymbol{MS_{ST_x}}$ = market share per sub-technology

Primary and Secondary Supply Estimations for Copper, Nickel and Lithium

There are significant obstacles related to estimating future supply with certainty due to a variety of factors that can affect production. This is especially the case for the period beyond the timeframe during which supply can be assumed to be relatively inelastic due to lead development times of future mining projects for each material. To estimate the future supply of copper, nickel and lithium, we use projected supply per future mining project provided by S&P Global (2022b). We use the estimations for the period 2021 to 2030 for future primary supply of copper and Lithium Carbonate Equivalent (LCE). To address the substantial discrepancy between the supply projections by S&P Global (2022b) and the reported production by the United States Geological Survey for global nickel production, we also extend the historical rate of supply increase from 2011 to 2019 to the period 2021-2030 to derive and estimate potential future primary supply. S&P Global (2022b) project falling supply after 2030, possibly due to the lack of already planned projects within this period. To overcome this limitation and create a proxy for future supply, we again apply the projected growth rate of production between 2021 and 2030 to the period 2030-2040. It is important to note that the analysis does not attempt to predict future supply but instead aims to offer a hypothetical benchmark scenario against which the potential market impact from increased demand can be assessed.

In this context, it is essential to also assess secondary supply for each material in addition to new production (primary supply). The two principal factors that determine secondary supply are (i) End-of-Life (EOL) recycling rates (the percentage of material in discards that is recycled) and (ii) the weighted lifespan of the material in end-use sectors. Using the EOL recycling rates provided by Månberger & Stenqvist (2018), supplemented by UNEP (2011) where necessary, we use the lifespans of all low-carbon technologies as a proxy to estimate secondary supply of each used material, and to estimate the lifespan within end-use sectors. This approach is chosen because of the difficulties in determining the different average lifespans of end-uses, weighed by end-use. However, this is likely to lead to an overestimation of supply, particularly in the near-term where substantive improvements in recycling rates are unlikely. Compared to the results by the IEA (2021a), our estimates for secondary supply are higher, yielding more conservative results that partially offset the assumption of static recycling rates in the future. Because recycling rates are heavily determined by substantial and stable increases in prices of commodities to make increased recycling financially viable, we do not assume an increase of the rate.

$$SS_e = RR \, . \, P_{t-ls} \qquad (10)$$

Where $\boldsymbol{SS_e}$ = secondary supply per material, $\boldsymbol{RR}$ = recycling rate, $\boldsymbol{P_{t-ls}}$ = production at time of material lifespan

5. Assessment of Transition-Critical Materials (TCMs) and potential bottlenecks in the NGFS Scenarios

Employing the methodology outlined above, this section conducts a three-fold analysis to assess the criticality of the focus TCMs, the implied material demand under the different NGFS

Scenarios and the demand increases in the context of projected supply. First, and starting from the original list of 27 TCMs, nine focus-materials are identified in order to, in a second step, estimate the future demand for these focus TCMs. In a third step, we compare the estimated demand with projected supply for a subset of three materials. The aim of this analysis is to examine supply-demand imbalances that may lead to material bottlenecks that could have consequences for commodity prices and financial risks. The focus is placed on bottlenecks because of their implications for the availability and prices of TCMs, and therefore for the viability of the different climate transition pathways.

5.1 Assessment of Transition-Critical Materials' criticality

The development of an individual risk profile for each of the 27 TCMs (Table 1) enables us to assess the comparative criticality level of the materials. This assessment, summarised in Table 3, offers a broad overview of the supply chain and demand pressures on TCMs, and enables us to further narrow down the selection of focus materials for the demand-side analysis.

Based on the assessment, we identify nine materials that are most exposed to demand-induced pressures, namely cobalt, copper, graphite, lithium, manganese, molybdenum, nickel, REEs and vanadium. Because of our focus on future material demand stemming from different climate transition scenarios, the demand-induced risk factors (transition demand risk, cross-cutting risk and substitutability risk) play the primary role for the identification of the nine TCMs. The identified sub-set of nine TCMs therefore serves as foundation for the second part of the analysis outlined in Section 5.2.

Furthermore, the identification of the seven supply risk factors and three demand risks factors as the main variables determining the supply availability, as well as demand-induced pressures, already point toward potential bottlenecks that could occur during the low-carbon transition. It is also worth noting that all materials are exposed to substantial pressures and any may face bottlenecks over the duration of the low-carbon transition. On the supply risk factors, the spatial distribution of material resources is considered part of 'material reserves', 'extraction' and 'refinement', while the geography-specific dynamics of materials are considered under the 'investment risk' and 'water stress' indicators. Moreover, the inclusion of secondary supply in the form of 'recycling rates' indicates the current dependency on primary supply to meet material demand. The demand-side variables are derived from our estimates of the increase in TCM demand between 2021 and 2030 under a 'Net-Zero 2050' scenario (outlined in detail in Section 5.2), which is noted as 'transition demand risk'. 'Cross-cutting risk' reflects the number of relevant transition technologies that require a specific material. 'Substitutability risk' represents the substitutability of sub-technologies, specifically the substitutability of different technologies within a technology type, and is informed by a review of the relevant literature.

Table 3. Criticality assessment of the 27 TCMs

	Primary Supply Factors						Secondary Supply Factors	Demand Factors		
Material	Reserves Concentration	Extraction Concentration	Refining Concentration	Country Risk Profile	Water Stress Risk	Lead Development Times (Years)	Recycling Rates (%)	Transition Demand Risk	Cross-Cutting Risk	Substitutability Risk
Aluminium/Bauxite	0.54	0.58	0.67	1.69	2.95		0.57	2.53	6	High
Cadmium		0.55	0.60		3.29		0.15	1.33	2	Low
Chromium.[6]	0.93	0.74	-	2.00	3.69		0.90	2.33	7	Very High
Cobalt	0.77	0.78	-	1.86	0.27	12	0.40	7.36	3	High
Copper	0.44	0.49	0.55	1.31	3.73	16.4	0.60	6.68	9	Very High
Gallium		0.99	-		3.25		0.15	1.39	1	Low
Graphite (Natural)	0.73	0.82	-	1.77	2.71			6.37	1	High
Hafnium							<0.01	2.19	1	Low
Indium			0.86				0.40	1.59	2	Low
Lead	0.68	0.60	-	1.23	3.30	14.1	0.72	1.48	2	Low
Lithium	0.75	0.87	-	1.21	3.57	5.5	0.10	7.29	2	Very High
Magnesium	0.48	0.81	-	1.92	3.02			1.58	2	Low
Manganese	0.78	0.59	-	1.71	2.48		0.53	5.02	6	High
Molybdenum	0.77	0.78	-	1.45	3.48		0.30	2.12	5	High
Nickel	0.61	0.56	-	1.58	2.68	12	0.60	6.57	7	Very High
Niobium	1.00	0.99	-	1.68	0.88		0.53	9.23	3	Medium
Rare Earth Elements.[7]	0.73	0.84	-	1.56	2.86		<0.01	3.56	2	High
Selenium	0.59		0.74	1.81			<0.05	1.39	1	Low
Silicon		0.79	-		2.99			2.90	2	Very High
Silver	0.50	0.50	-	1.41	3.51		0.80	2.82	3	Low
Tantalum	0.99	0.73	-	1.22	0.27			3.54	1	Low
Tellurium	0.35		0.82	1.27			<0.01	1.32	2	Medium
Tin	0.54	0.69	-	1.58	2.52		0.75	2.08	1	Low
Titanium	0.67	0.89	-	1.42	2.63		0.91	2.08	1	Low
Tungsten	0.70	0.90	-	1.63	3.11			2.08	1	Low
Vanadium	0.84	0.93	-	1.59	2.90		<0.01	29.40	3	High
Zinc	0.54	0.55	-	1.29	3.29	14.1	0.40	1.53	4	Medium
Average	0.67	0.74		1.55	2.75	16.9	0.40	4.32	3	
Scale	0-1	0-1	0-1	0-4	0-4	Years	0-1	Indexed to 2021 Demand	1-10	Low-Very High

Source: Compiled by authors. Note: Colour coding for the supply factors by quartiles, red denoting the highest degree of criticality. Demand factors are colour coded based on a relative qualitative assessment of the indicators. For an explanation of the calculations, please see section 3.1.

The selection of the nine 'focus' materials for the demand analysis in section 4.2 is based on our findings of the greatest demand-induced pressure from the transition. Given to focus on the demand side in the analysis below, the selection concentrates on the demand-side pressures for each material, namely transition demand risk, cross-cutting risk and

[6] Chromium was not selected in the focus minerals group due to data limitations. However, it has a very high overall risk assessment and ought to be considered highly 'critical' regarding risk potential.

[7] Rare Earth Elements consist of the following elements: Dysprosium, Neodymium, Praseodymium, Terbium, and Yttrium

substitutability risk. This criticality assessment serves two purposes within the paper. First, it offers a broad overview of the supply chain and demand pressures on TCMs. Second, it enables us to select the focus materials for our demand-side analysis.

5.2 Assessing demand for Transition-Critical Materials (TCMs) in the NGFS scenarios

Building on the identification of the nine focus materials, we examine the demand-side risks from the transition to net zero within the 'Net Zero by 2050' and 'Delayed Transition' scenarios, noting that there is uncertainty about how energy technologies will develop, their material requirements, as well as the market shares of different technologies, and the global trajectory of the low-carbon transition. Given that future supply and demand of metals cannot be predicted with substantial confidence, different scenarios with different assumptions concerning the penetration of low-carbon energy technologies can be envisaged (IPCC, 2022; IEA, 2020).

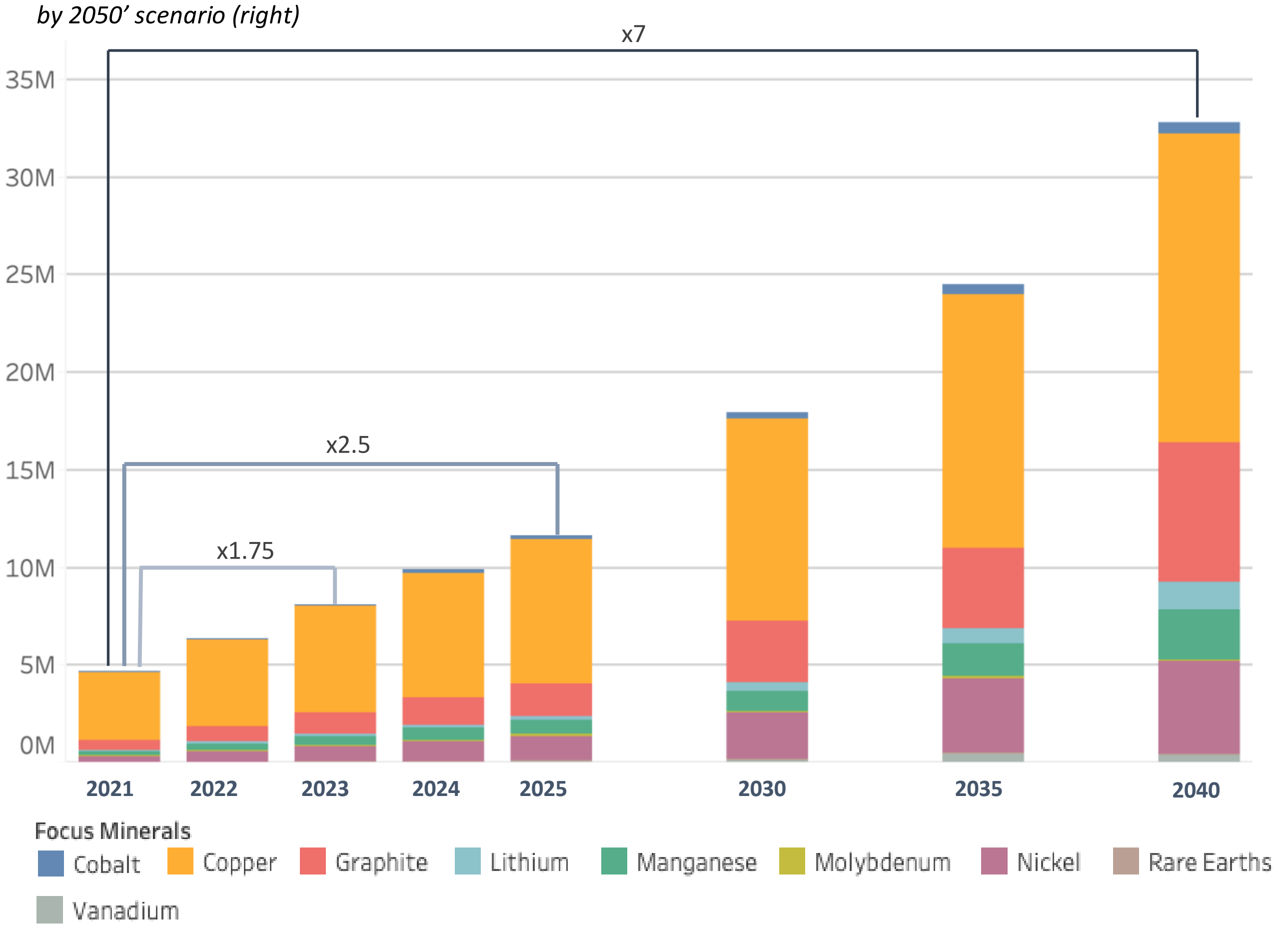
With a focus on potential supply-demand dynamics and 'bottlenecks', the empirical analysis focuses on future material demand between 2021 and 2040 under the 'Net Zero by 2050' and 'Delayed Transition' scenarios. Both scenarios require a sharp upscaling in low-carbon technology deployment, however, at different times with differing constraints and macroeconomic conditions. The 'Net Zero by 2050' scenario represents an 'orderly transition', requiring significant upscaling in the rate of low-carbon technological deployment prior to 2025. The 'Delayed Transition' scenario resembles a 'disorderly transition' and assumes minimal annual capacity addition in low-carbon technologies prior to 2030, followed by a significant increase in the rate of annual capacity additions. Both scenarios mitigate the most severe physical climate impacts by restricting global warming to 1.5°C and 2°C, respectively. Great uncertainties remain regarding the transition to a net zero economy. Hence, these results should not be viewed with too high a degree of confidence or as a forecast, but as an exploratory exercise to assess potential risk. (See Appendix 4 for further details on the limitations).

TCM demand of the 'Net Zero by 2050' scenario

To estimate the implied material demand under the 'Net Zero by 2050' and 'Delayed Transition' NGFS scenarios, we estimate, first, the demand increase of key materials over the period 2021-2040; second, the technology split in demand over the observed period; and finally, the relative increase in per material demand in 5-year step intervals (See Appendix 3 for step 2 and 3).

Figure 1 illustrates both, the total demand at 5-year intervals (2030, 2035, 2040) and the annual increases in material demand (from 2021-2025) for the 'Net Zero by 2050' scenario. Assuming a linear increase in annual capacity additions, the 'Net Zero by 2050' scenario projects capacity additions to increase 1.75 times between 2021 to 2023, with an increase of 2.5 times between 2021 and 2025. Under this scenario, there is a particularly significant increase in demand for vanadium and cobalt, demand for which approximately increases 11 times and 4 times, respectively. Additionally, total absolute demand increases from approximately 4.7Mt in 2021 to over 11.6Mt in 2025.

Figure 1: 2021-2025 year-on-year (left) and 2030, 2035, and 2040[8] annual demand for the TCMs in the 'Net Zero by 2050' scenario (right)



Total material demand also significantly increases over the 5-year intervals with total demand for the nine focus materials more than doubling from 2025 to 2035 compared with 2025, and increasing 7 times between 2021 and 2040. For this longer time horizon, the relatively two most affected materials are vanadium and lithium, for which demand is approximately 6 and 4 times higher in 2035 compared to 2025, respectively. This significant increase of demand for vanadium in both the short- and long-term can also be explained by its current relatively low deployment in low-carbon technologies compared to other critical materials. Additionally, both nickel and cobalt are subject to an increase in demand by over 4 times over the same period.

Because copper it is already mined in substantial quantities, the increases in demand are less significant. However, absolute annual demand increases by approximately 5.7Mt between

[8] Post-2035 annual EV demand is assumed to be constant year-on-year due to data limitations. Please see Appendix for further details.

2025 and 2035, which could nonetheless cause significant demand-induced pressures for copper (see Appendix 2). Absolute annual demand for all focus materials over the observed period increases from 4.7Mt in 2021 to 32.8Mt in 2040. As discussed below, both, the relative and absolute increases in material demand under the 'Net Zero by 2050' scenario, may have a significant impact on the commodity prices of these materials. This is particularly pertinent in the short-term, where demand increases are significant, and supply is likely to be price inelastic.

TCM demand of the 'Delayed Transition' scenario

For the NGFS 'Delayed Transition' scenario, we assess the annual demand growth between 2031 and 2036, the timeframe where demand starts to significantly increase, as well as at 5-year intervals for 2021, 2025, and 2040 (Figures 2 and 3). We estimate TCM demand with and without the inclusion of EVs, thereby creating two further 'sub-scenarios', 'Delayed Transition including EVs' (DS) and 'Delayed Transition excluding EVs' (DS2). This is necessary due to the significant misalignment between the model narrative and the observed distortion of the rate of demand increases. For example, within the 'Delayed Transition' scenario, almost all deployment of climate mitigation technologies is delayed until post-2030. However, the projected amount of EVs by EV Volumes (2022) indicates a significant deployment of EVs prior to 2030, which is partially driven by the current policies supporting EV deployment. These projections by EV Volumes (2022) do not match the narrative of the 'Delayed Transition' scenario, and consequently distorts the necessary rate of increase for low-carbon technology deployment post-2030 in the scenario.

The total demand (including EVs) for the nine focus materials under a 'Delayed Transition' scenario increases from 1.7Mt to 4.6Mt between 2021-2025, which is significantly less than the demand in the same timeframe under the 'Net Zero by 2050' scenario. Between 2031-2035, we estimate demand to increase by 2.1 times if EVs are included (Figure 2), and 3.4 times if EVs are excluded (Figure 3). Under sub-scenario including EVs, the rate of increase is therefore lower than in the 'Net Zero by 2050' scenario. However, absolute annual demand increases by 14.3Mt (including EVs) and 10.6Mt (excluding EVs) over the same period. In absolute terms, annual demand under the 'Delayed Transition' scenario (including EVs) is therefore greater than under the 'Net Zero by 2050' scenario by 2035.

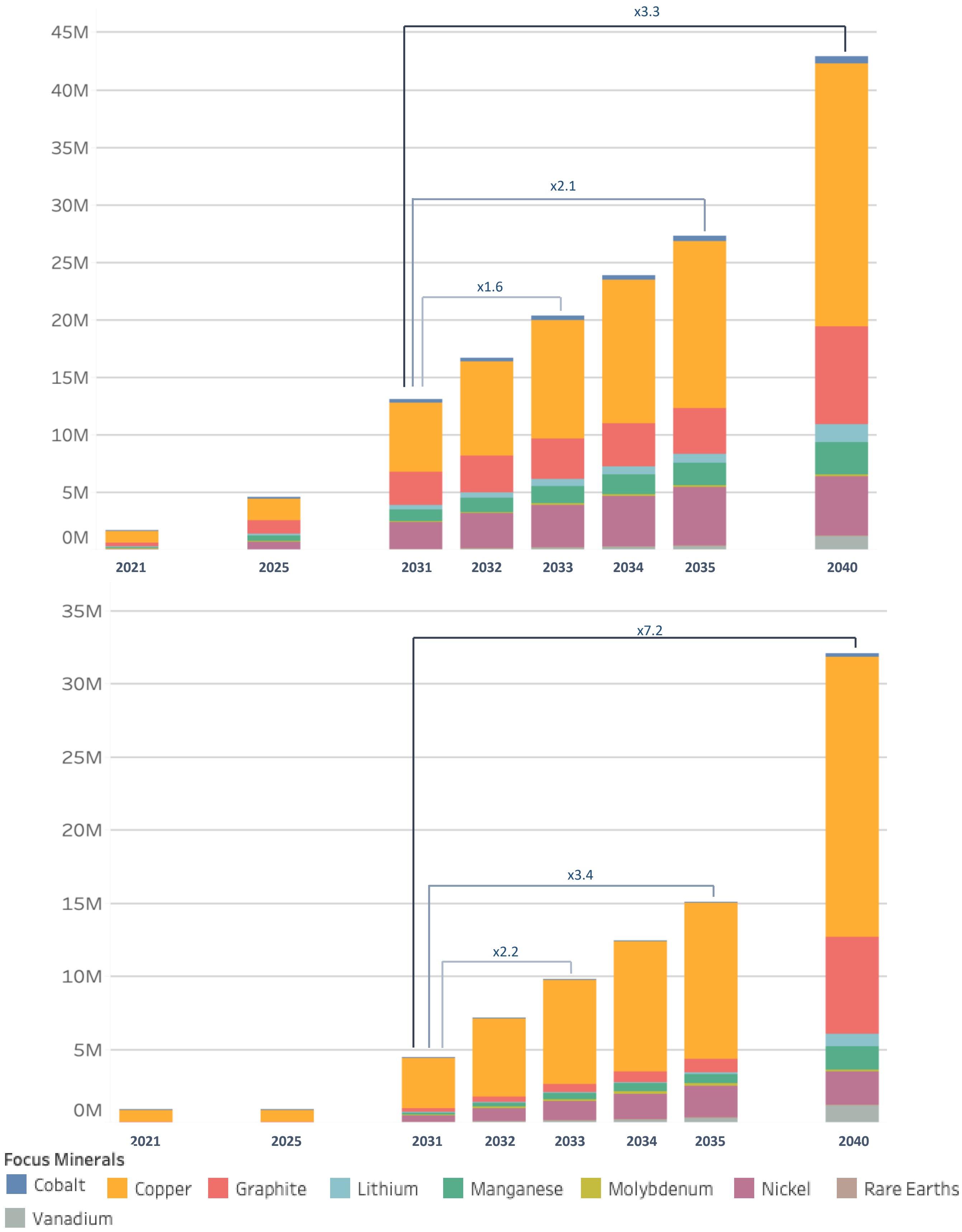
Under the 'Delayed Transition' scenario, the absolute annual increases are necessarily substantially larger after 2035. Between 2035 and 2040, demand for the focus materials in low-carbon technologies increases by 15.6Mt including EVs (Figure 2), and 17Mt excluding EVs (Figure 3)[9]. This faster increase in demand over the observed timeframe could have a more disruptive impact on the market. Furthermore, in the period 2036-2040, material

[9] This is a consequence of the distortion effect which occurs from the inclusion of EVs, because the 'Delayed Transition' scenario assumes capacity deployment mainly occurs post-2030, whereas the EV Data Centre assumes EVs will be substantially deployed prior to 2030.

demand is 26.4 times higher compared to the period 2021-25 (excluding EVs), highlighting the abrupt material demand increases necessary under the ‘Delayed Transition’ scenario.

As illustrated by Figure 3, the relative annual demand increase for the nine materials is substantially larger with the exclusion of EVs. Between 2031 and 2035, vanadium (6.7 times), nickel (4.7 times) and copper (3 times) are subject to the greatest increase in demand, approximately. In absolute terms, annual copper demand increase by 7.2Mt between 2031 and 2035 (excluding EVs). Over the entire observed period, absolute demand for all focus materials increases from 1.7Mt to 42.9Mt (including EVs) and from 0.94Mt to 32.1Mt (excluding EVs). By 2040, annual demand excluding EVs under a ‘Delayed Transition’ scenario is roughly equivalent to demand under a ‘Net Zero by 2050’ scenario with the inclusion of EVs. The demand-induced pressures prior to 2030 are minimal, indicating potential lower price and inflationary pressures on commodity prices in the short-term. However, both sub-scenarios display substantial demand increases after 2030, with greater or equivalent annual demand by 2040 compared with the ‘Net Zero by 2050’ scenario. For further details on the technology-and material-specific demand, see Appendix 3.

Figures 2 & 3: 2031-35 year-on-year demand, and annual demand at five-year intervals (2021, 2025, 2040) under a 'Delayed Transition' scenario including EVs (DS) and 'Delayed Transition' excluding EVs (DS2).



For further analysis on the technology-and material-specific demand, please see Appendix 3.

5.3 The TCM supply-demand nexus for lithium, nickel and copper

Our estimation of the supply-demand mismatch for three focus TCMs, namely lithium, copper and nickel, provides further insights into the potential future material bottlenecks under the two NGFS scenarios. The selection of these three materials is based on their relevance for the climate transition, as well as data availability. The focus on the rate of increase as a proportion of supply provides an initial indication of the supply-demand mismatches that could have implications for financial and price stability. For the 'Delayed Transition' scenario, the sub-scenario that excludes EVs (DS2) is also considered due to the distortionary effect of EVs on the model outputs. In this context, and for the final time-period 2036-40, EV volumes are assumed by us to be the same as in 2035 for the 'Net Zero by 2050' and 'Delayed Transition' (including EVs) scenarios, yielding a conservative estimate. Figures 6, 7 and 8 illustrate the demand-supply nexus for the three materials, while the connected tables only include low-carbon technological demand as a proportion of total supply at 5-year time intervals.

The demand illustrated in Figure 6, 7 and 8 for the three materials represents only the total demand for transition technology additions and does not including demand from other sectors. However, the illustrated supply is the total supply that will have to meet the demand from all economic sectors. Hence, the projected supply of nickel and copper illustrated in Figure 7 and 8 is significantly larger than the expected demand stemming from the low-carbon transition, indicating the considerable importance for and demand from other sectors in the economy. Hence, bottlenecks may emerge with material impacts on prices.

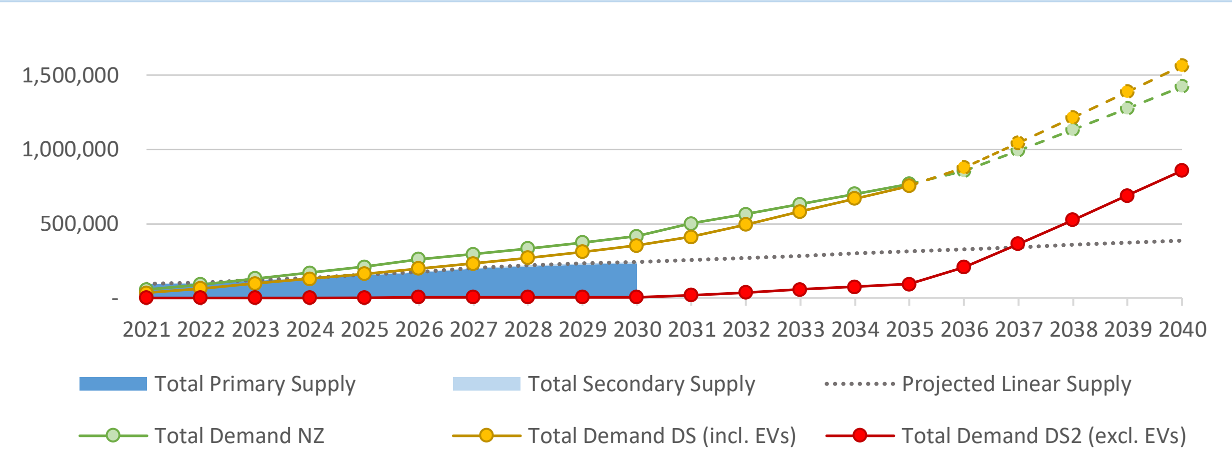
With this analysis, we focus on the rate of increase relative to total supply, which indicates whether price implications may occur originating from low-carbon technological demand. Where the rate of increase of material demand from low-carbon technological exceeds the projected supply for a material, it becomes relevant to consider how the excess demand is addressed by the market. If expected demand shifts occur on an intra-sectoral level, with technological exchanges, then this may have little impact on the commodity price (e.g., a transition from Internal Combustion Engine (ICE) vehicles to EVs). However, if excess demand is compensated through inter-sectoral shifts in demand, there could be a substantial impact on the commodity price, which would also depend on the relative price elasticities of demand from the relevant sectors (e.g., a shift in copper demand from cooling equipment to electrical power generation). In case of an inter-sectoral shift, there would likely be a competition for resources between economic sectors and, ultimately, higher prices. Subsequently, these price increases may jeopardise the financial viability of low-carbon technology projects through higher material costs, and lead to higher credit risks for financial institutions. Moreover, if coupled with supply-side shocks, substantial price volatility could contribute to financial risks within commodity markets through basis risk (e.g., the risks that emerge when futures contract prices do not move in correlation with the prices of the underlying assets, leading to mismatches in hedged positions).

The Supply of and Demand for Lithium

Under both NGFS scenarios, as illustrated by Figure 7, the estimated material demand for lithium starts to exceed projected supply by 2023 and 2025, respectively. The proportion of supply that the transition requires is greater in the observed period under the 'Net Zero by 2050' scenario, with estimated demand reaching 133.49% of projected supply by 2025. However, the rate of material demand increase is greater under the 'Delayed Transition' scenario, leading to a steeper rate of increase, with 'Delayed Transition' scenario-demand almost equalling 'Net Zero by 2050' scenario-demand by 2035. In the 'Delayed Transition' scenario excluding EVs (DS2), we observe little demand until 2030, illustrating that the near-term demand for lithium is primarily driven by the deployment of EV technology.

However, after 2030, there is significant demand for lithium under the 'Delayed Transition' scenario excluding EVs from other technologies (not EVs), namely freight transportation and energy storage technologies. Under this scenario, there is also an extremely significant rate of annual demand increase for lithium after 2035. We find estimated demand to increase from approximately 30.2% of total supply to over 220% between 2035 and 2040, exceeding our projected linear growing supply by 2037. Under all three scenarios, the estimated future demand increase for lithium vastly outstrips the projected increase in supply, which may result in sharp increases of the price of lithium. This phenomenon is already materialising with prices for Lithium Carbonate Equivalent (LCE) having increased by between 300% and 500% year-to-date between mid-2021 and mid-2022, pushed in large part by the spike in EV sales in China (S&P Global, 2022b; Kimani, 2022).

Figure 6: Total supply for lithium against demand from low-carbon technological deployment in the 'Net Zero by 2050' and 'Delayed Transition' scenarios, tonnes (t)



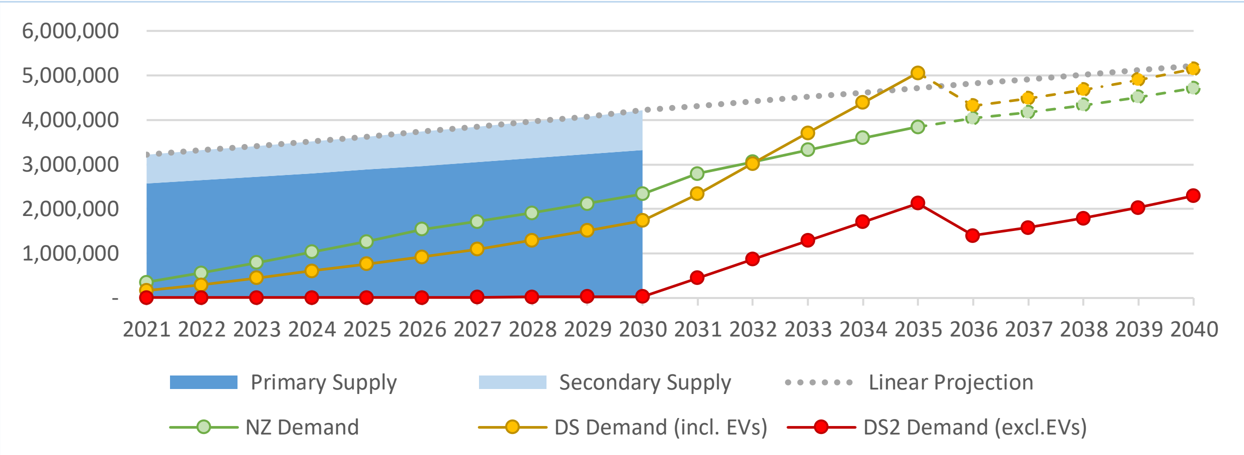
Scenario	2021	2025	2030	2035	2040
NZ	59.30%	133.49%	172.38%	244.49%	367.84%
DS	37.61%	103.61%	146.27%	240.53%	404.19%
DS2	1.82%	1.10%	2.46%	30.20%	221.62%

Source: Compiled by authors. Note: 'Net Zero by 2050' scenario (NZ), 'Delayed Transition' scenario including EVs (DS), 'Delayed Transition' scenario excluding EVs (DS2). Table: Demand as a proportional % of total supply under NZ, DS and DS2 scenarios. Dashed lines for the estimated material demand are used to reflect the assumption that for the final time-period, 2036-40, EV volumes are the same as the period 2031-35 for the 'Net Zero by 2050' and 'Delayed Transition' scenarios.

The Supply of and Demand for Nickel

Concerning nickel, as illustrated in Figure 7, we find the potential for significant market disruption under 'Net Zero by 2050' and the two 'Delayed Transition' scenarios. While the market disruption is expected to be more significant under 'Net Zero by 2050' scenario before 2030, after 2030, the rate of demand increase is more significant under the 'Delayed Transition' scenarios, with demand from low-carbon technological deployment increasing from 41.20% of total projected supply in 2030 to over 100% of total projected supply by 2035. Even under the 'Delayed Transition' scenario excluding EVs (DS2), we find the proportion of supply demanded by the transition increase from 0.82% to 43.34% of total projected demand between 2030-35. These increases in demand rates, proportional to supply, indicate a potential for significant market disruptions that could occur when the share of demand rapidly shifts from other sectors to low-carbon technologies. This swift shift in sectoral demand would be reflected through higher nickel prices and require material demand from low-carbon technologies to be price inelastic if the scenarios are to be realised. In the 'Delayed Transition' scenarios that include and exclude EVs, the 'demand peak' in 2035 reflects the sharp uptake of geothermal technology in the 2031-35 period, which is particularly nickel-intensive (approximately 100,000 t/GW, according to our calculations).

Figure 7: Total supply for nickel against demand from low-carbon technological deployment in the 'Net Zero by 2050' and 'Delayed Transition' scenarios, tonnes (t)



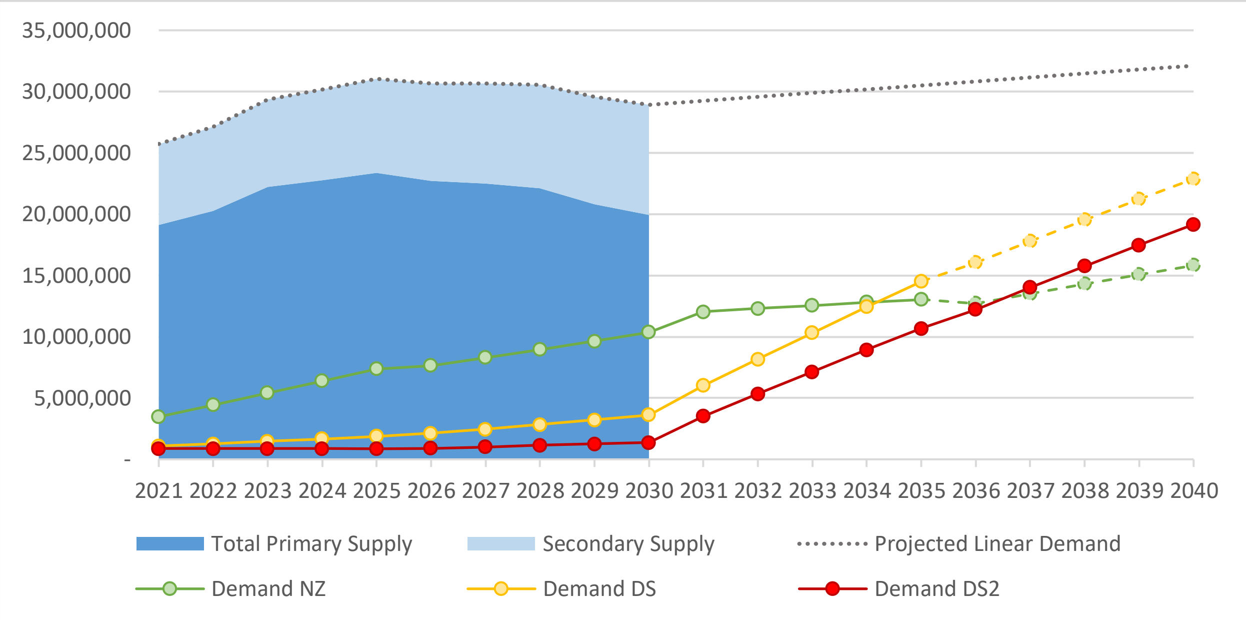
Scenario	2021	2025	2030	2035	2040
NZ	11.06%	34.95%	55.51%	81.49%	90.43%
DS	5.20%	21.10%	41.20%	107.18%	98.70%
DS2	0.38%	0.34%	0.82%	43.34%	44.01%

Source: Compiled by authors. Note: 'Net Zero by 2050' scenario (NZ), 'Delayed Transition' scenario including EVs (DS), 'Delayed Transition' scenario excluding EVs (DS2). Table: Demand as a proportional % of total supply under NZ, DS, and DS2 scenarios. Dashed lines for the estimated material demand are used to reflect the assumption that for the final time-period, 2036-40, EV volumes are the same as the period 2031-35 for the 'Net Zero by 2050' and 'Delayed Transition' scenarios.

The Supply of and Demand for Copper

Figure 8 shows that between 2021 and 2025, the demand for copper increases most significantly under the 'Net Zero by 2050' scenario, with the proportion of supply increasing from 13.49% to 23.77%. However, after 2030, the 'Delayed Transition' scenario points towards potential disruptions and imbalances. While copper may not seem particularly at risk, unlike other materials that were relatively unused until recently and now need to see a sharp rise in their extraction, copper has been widely deployed to accompany the growing electrification of the world economy. Consequently, estimated demand for copper from low-carbon technological deployment is below the projected supply, with demand approximately equal to 43% and 48% of total supply by 2035 under the 'Net Zero by 2050' and 'Delayed Transition' scenario including EVs, respectively. However, the rate of increase and proportion of supply demanded by the transition, which are most important in the context of price volatility and the relative cost of low-carbon technological deployment, point towards potential disruptions. The rate of increase under the 'Delayed Transition' scenario excluding EVs between 2030 and 2035, with the proportion of supply demand increasing from 4.73% to 35%, may have substantial implications for the price of copper. Furthermore, because copper is one of the most widely used materials across a typical advanced economy, sudden increases in demand will likely translate to higher prices.

Figure 8: Total supply for copper against demand from low-carbon technological deployment in the 'Net Zero by 2050' and 'Delayed Transition' scenarios, tonnes (t)



Scenario	2021	2025	2030	2035	2040
NZ	13.49%	23.77%	35.90%	42.76%	49.25%
DS	4.25%	6.06%	12.50%	47.57%	71.25%
DS2	3.41%	2.77%	4.73%	35.00%	59.70%

Source: Compiled by authors. Note: 'Net Zero 2050' scenario (NZ), 'Delayed Transition' scenario including EVs (DS), 'Delayed Transition' scenario excluding EVs (DS2). Table: Demand as a proportional % of total supply under NZ, DS, and DS2 scenarios. Dashed lines for the estimated material demand are used to reflect the assumption that for the final time-period, 2036-40, EV volumes are the same as the period 2031-35 for the 'Net Zero by 2050' and 'Delayed Transition' scenarios

In summary, we find that across all three metals, the 'Net Zero by 2050' scenario presents near-term demand pressures, whereas the 'Delayed Transition' scenario has minimal demand pressure prior to 2030, but creates significant pressures because of the abrupt increase in demand after 2030. Under both scenarios, this increase in the rate of annual demand increases could present substantial challenges for the supply-demand balance. Furthermore, it could create significant price volatility and raise the risk of the scenario failing to be realised, creating significant transition risks. However, the scenarios present a critical trade-off between possibly increased price pressures in the near-term and more likely greater price increases coupled with recurrent shortages in key materials post-2030.

Regarding prices, the 'Net Zero by 2050' scenario is likely to create inflationary demand pressures for these materials over a shorter time horizon, while the 'Delayed Transition' scenario would likely bring greater inflationary impacts over the long-term in addition to being associated to greater physical climate risk in case of a failure to realise the 'Delayed Transition' scenario. In the context of imperfect information (and foresight), it is also unlikely that the price pressures under the 'Delayed Transition' scenario would be mitigated through an expansion of supply to meet expected demand prior to 2030. Due to the inherent uncertainty of the transition scenarios, 'pre-planning' future demand based on scenario narratives is not realistic.

Appendix 4 provides a more detailed account of the results, supply projections and risk factors discussed in Section 2. In providing an initial assessment and highlighting avenues for further research, it also highlights the role of the degree of substitutability and criticality for the transition, as well as other factors that could mitigate or increase potential bottlenecks.

6. Financial and price stability implications of Transition-Critical Materials

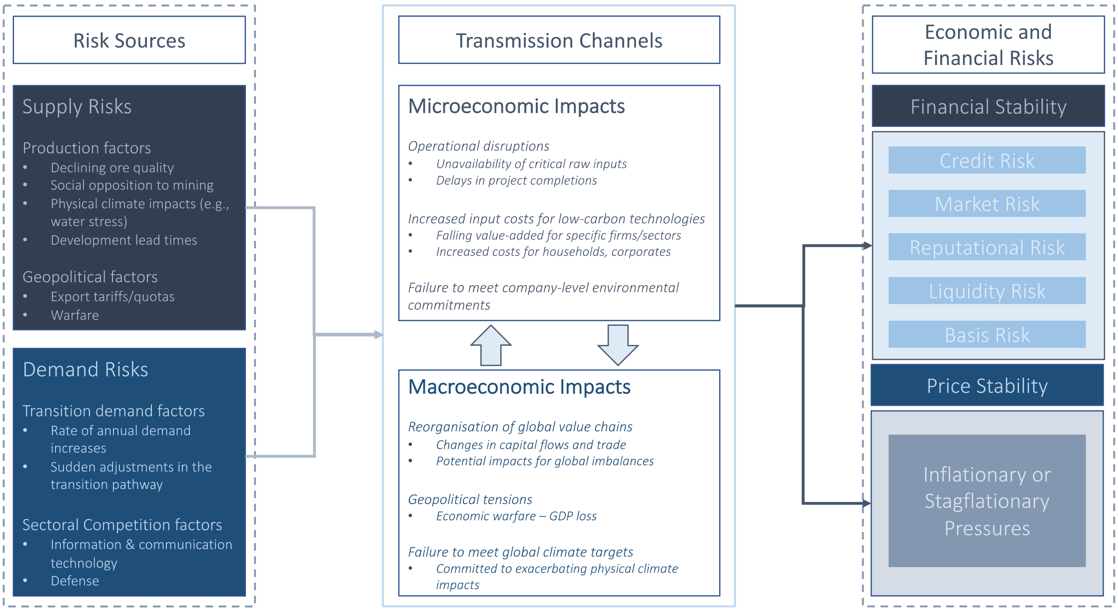
Under both NGFS scenarios, the production and supply of TCMs would have to significantly increase to meet the demand created by the projected capacity additions for low-carbon technologies. The rate of demand increases under the 'Delayed Transition' scenario is particularly steep, which could increase the probability of price shocks through the materialisation of supply-demand imbalances. Furthermore, the realisation of the transition could be affected, if significant supply-side or demand-induced shocks occur, adding further to transition risks (or even jeopardising the transition, thereby contributing to physical risks). The prices spikes, driven by low-carbon technology deployment, would also spill over into other material-dependent sectors and could place broader inflationary pressures on the global economy. The presented evidence therefore indicates implications for the core objectives of central banks of guaranteeing price as well as financial stability, both of which could be affected by the additional transition risks related to the supply inelasticity of TCMs in the face of a dramatic increase in demand.

(i) There are several different transmission channels through which the identified sources of TCM supply and demand constraints-related risks could affect price and financial stability. As illustrated in Figure 9, three initial channels can be identified that also offer a starting point for further research. Specific TCMs and their value chains will be particularly under pressure, exposing dependencies and related firms and/or sectors to significant transition risks. Further research should assess this channel in more depth to create a foundation for the investigation of financial institutions' exposure to these firms and sectors.

(ii) There could be implications for the reorganisation of global value chains related to TCMs and associated effects on countries' balance-of-payments, with potential impacts on global imbalances. Further analysis would have to be expanded to an international scale to explore links and implications.

(iii) Supply- and demand-side constraints may lead to increases in price volatility and inflationary pressures. Further research exploring elasticities and inflationary implications can build on first research exploring this link (Boer et al., 2021).

Figure 9. Transmission of supply- and demand-side constraints towards economic activity, and potential impacts of price and/or financial stability



Source: Compiled by authors.

6.1 Financial stability impacts

Given the different risk profiles of the TCMs, there are significant uncertainties relating to the financial risk and stability implications resulting from supply-demand tensions, calling for a comprehensive risk assessment and analysis of the related value chains, starting from extraction to their transformation and integration into specific clean energy technology.

Generally, the TCM supply and demand constraints may lead to the materialisation of a variety of financial risks. The pressures from 'sunrise' transition industries and the decline of 'sunset' industries may thereby have spill-over impacts for other sectors and culminate to create broader financial risks (Semieniuk et al., 2020). More specifically, supply-side shocks may exacerbate supply-demand imbalances and create financial risks. For example, weather-related supply impacts, such as water scarcity, may substantially reduce production or geopolitical events may suddenly reduce the supply of TCMs (Olivetti et al., 2017; Rüttinger et al., 2020). These risks could create supply-side price shocks for commodities, particularly in locations where production is geographically concentrated. The increased costs may in turn affect the financial viability of new low-carbon technological deployment projects and affect the credit risk of firms if their projects become unviable. This is particularly prevalent for energy generation projects, where development times can lag due to frequent delays (IEA, 2021b).

The additional input costs created by short-term price volatility in TCMs may therefore currently not be factored into the initial economic cost assessment of a new project. For example, the impact of supply-side price shocks from REEs on the financial returns of clean energy industries has already been documented (Baldi et al., 2014). Additionally, and if climate patterns persist, the physical stranding of production assets may occur in locations with limited and scarce water availability. If this is the case, and considering the demand analysis presented here, the 'Delayed Transition' scenario may be subject to more significant supply-side shocks originating from water stress due to the higher material demand in later time-periods where physical climate risks would be more pronounced. In turn, this may also lead to a deterioration of the financial position of affected companies with potential market implications for the connected firms and sectors in the value chains.

6.2 Economic and financial impacts

The discussed TCM-related risks and uncertainties caused by the reorganisation of value chains and changes to countries' balance-of-payments are also likely to have wider economic and financial impacts. Whether firms in producing countries benefit from the transition outlined under the different scenarios also depends on whether producing countries succeed in moving up the TCM value chain (e.g., moving from mining and refining to processing and manufacturing), or whether these higher value processes occur in other countries. Changes in countries' trade, and by extension their balance of payments, resulting from the clean energy transition may create structural challenges for some countries. This will be particularly the case for countries where 'sunset' industries currently dominate the economy and significantly contribute to GDP growth. Economic decline in previously export-led growth countries, coupled with the rapid increase of exports from other countries, will shift the balance of the global economy and may give rise to economic, geopolitical and financial risks.

In this context, Volz et al. (2021) suggest a conceptual framework to assess the material and technological position held by different countries in the global economy, differentiating between four country types, namely (i) a fossil-rich exporting country whose trade balance will be negatively impacted by the transition; (ii) a country that produces and exports capital goods (green technologies) needed for the low-carbon transition; (iii) a country endowed with the materials needed to manufacture the capital goods required for the low-carbon economy; (iv) and a 'purely' importing country, which will shift from importing fossil fuels to importing low-carbon capital goods in which TCMs are embedded. Based on the classification, the authors estimate potential impacts of the decarbonisation of the global economy on trade patterns, finding that under specific scenarios, the low-carbon transition could reinforce existing global imbalances, including, for example, a deepening of existing current account deficits and surpluses in the US and China, respectively.

Volz et al. (2021) also point toward the possibility that the low-carbon transition could significantly impact the balance of payments of both exporting and importing countries, and the size and direction of international financial flows. For instance, as foreign direct investments (FDIs) from fossil fuel exporting countries decline, FDIs coming from countries that produce low-carbon capital goods and/or TCMs could significantly rise. However, the reinvestment of surpluses between existing fossil fuel exporting countries and future low-carbon technology exporters may differ, including because of the geopolitical considerations outlined in this paper.

6.3 Price stability impacts

In addition to the financial stability implications and risks, and as outlined in Section 5, potential bottlenecks related to TCMs could also have implications for price stability. While attracting less attention in central banks than fossil fuel prices, strong material price fluctuations, as observed since the beginning of the 2000s, can also affect the overall price level. This concern has recently also been recognised and highlighted by central banks (Schnabel, 2022; (Menon, 2022)Menon, 2022).

Historically, the impact of material prices on inflation has often been rather small. For example, for the Euro Area, Landau & Skudelny (2009) estimate that a 10% increase in industrial raw material prices could lead to a rise in Euro Area core inflation by 0.15% over a 3-year horizon. While these estimates are relatively small, the inflationary impact of material prices might become larger in case material shortages lead to an intensification of bottlenecks. Boer et al. (2021) provide a first quantification of the potential impact of the energy transition on material prices by estimating the impacts as a sequence of demand shocks in separate structural Vector autoregression (VAR) models for copper, nickel, cobalt and lithium. The authors find inflation adjusted prices of the four TCMs to potentially reach "peaks similar to historical ones but for an unprecedented, sustained period of roughly a decade" (Boer et al., 2021, pp. 4-5). The research highlights the importance of the differences in material demand under transition scenarios where steeper material demand increases will likely translate to higher commodity prices. Higher prices could in turn offer a difficult trade-off for governments (and by extension central banks), between greater inflationary pressures and increased costs of living in the short-term, or failure to realise climate objectives and committing to greater climate physical impacts in the medium-term.

While Boer et al. (2021) focus on the potential long-term price trends of TCMs, their prices could also be subject to short-term volatility. Generally, the production of industrial metals relies on complex market organisation that is affected by the ease of access to finance. This process is also shaped by the metals' ability to hold value (for carry trades), which encourages commodity trading houses to use financial leverage to expand their activity, thereby enhancing the co-movements of metal prices with financial indices (Shamsher, 2021; Saishree & Padhi, 2022).

This financialisation process can also contribute to an increase of the pro-cyclicality of metal prices, which react strongly to the economic cycle and are vulnerable to short-term shocks in the financial system. Furthermore, inventory dynamics play an important role in shaping the reaction of market participants to supply and demand shocks. For example, a change in the market's perception of short-term scarcity can lead to abrupt changes in material prices. Highly relevant in this context is the degree of persistence of the shocks. For temporary scarcity shocks, an adjustment through inventories could ease the pressure on prices, which would gradually return to their initial or equilibrium level. For instance, Roache & Erbil (2011) empirically show for six metals (including copper and nickel) that, in a tight physical market, even a small supply disruption can have large price effects, which nonetheless tend to be short-lived. However, in the context of a more permanent scarcity of metals, inventories would unlikely be able to act as a buffer, in the case of which price increases could be more significant and above all more persistent.

In the context of central banking and monetary policy, further research on these different price dynamics and on how they could pass-through other sectors to consumers, thereby effectively resulting in potential 'greenflation' (Schnabel, 2022), is needed. While the share of specific TCMs in final consumption is often marginal, the contribution of material price changes to inflation mainly originates in their impact on the production and distribution chains. Therefore, and since TCMs are mostly relevant for industrial sectors, the effect of their prices on inflation is more significant in countries with a large industrial sector. However, higher metal prices raise firms' costs, which are likely to be at least partly passed on to consumers. Furthermore, the inflationary impact of TCM price changes is likely to also come from metal-intensive imported goods, the demand of which is expected to strongly increase.

Empirically, the estimation of the impact of TCM price increases on headline inflation will require reduced-form as well as model-based approaches. Reduced-form approaches can be used to assess the degree of pass-through at the different steps of the price transmission mechanism (e.g., from TCM prices to the price of parts and components, to production prices and ultimately to consumer prices). Model-based approaches can play a role in tracing the complexity of pricing behaviour of different actors through production and distribution chains, thereby drawing on detailed information about production technologies and international value chains. For example, world input-output tables could be used to analyse TCM prices in the context of cost-push inflation, as well as to distinguish between direct price effects through imported consumption goods, price effects coming from imported inputs necessary to produce the final goods, and amplification price effects transmitted through global value chains.

Going forward, central banks' core price and financial stability objectives will be affected by the TCM supply-demand nexus and the expected bottlenecks in the context of the transition. With the increasing demand of TCMs in new technologies (whether related to the transition or digitalisation), their share in final consumption will become larger, thereby increasing the impact of their prices on inflation. The expected higher and more volatile prices of TCMs warrant closer scrutiny by central banks in their price and wider macroeconomic stability assessment.

7. Conclusions

While the exact quantities and rates of annual increase in demand depend on the realised transition pathway and related level of climate ambition, it is clear that the low-carbon transition will significantly increase the demand for TCMs. Furthermore, there is a broad range of materials required for the deployment of the different low-carbon technologies and sub-technologies, each of which is exposed to specific supply-side risk and demand-induced pressure profiles. The analysis and estimates provided in this paper point toward the range of risks that the TCMs could be exposed to under two NGFS transition scenarios. It also offers insight into the relative 'criticality' of different TCMs, accounting for both supply and demand risk factors.

Nine TCMs are identified as most exposed to demand-induced pressures, namely cobalt, copper, graphite, lithium, manganese, molybdenum, nickel, REEs and vanadium. Estimating the demand for TCMs under the 'Net Zero by 2050' and the 'Delayed Transition' NGFS Climate Scenarios, we find that demand will rapidly increase under both scenarios.

Specifically, under the 'Net Zero by 2050' scenario, total absolute annual demand more than doubles from 2025 to 2035 compared with 2025, and increases 7 times between 2021 and 2040. Absolute annual demand over the observed period thereby increases from 4.7Mt in 2021 to 32.8Mt in 2040.

Moreover, under the 'Delayed Transition' scenario, in which we estimate TCM demand including EVs, we find total demand to increase from 1.7Mt to 4.6Mt between 2021-2025, and to increase by 2.1 times (including EVs) and 3.4 times (excluding EVs) between 2031-2035. Under the sub-scenario including EVs, the rate of increase is lower than in the 'Net Zero by 2050' scenario. However, absolute annual demand increases by 14.3Mt (including EVs) and 10.6Mt (excluding EVs) over the same period. However, between 2035 and 2040, demand for the focus materials in low-carbon technologies increases by 15.6Mt (including EVs) and 17Mt (excluding EVs), with material demand 26.4 times higher compared to the period 2021-25 (excluding EVs). In absolute terms, annual demand under the 'Delayed Transition' scenario (including EVs) is therefore greater than under the 'Net Zero by 2050' scenario by 2035.

Our estimation of the supply-demand mismatch for three focus TCMs, namely lithium, copper and nickel, provides further insights into the potential future material bottlenecks under the two NGFS scenarios. We find that for lithium, estimated material demand starts to exceed projected supply by 2023 ('Net Zero by 2050') and 2025 ('Delayed Transition'). For nickel, we find that under the 'Delayed Transition' scenario (including EVs), demand from low-carbon technological deployment increasing from 41.20% of total projected supply in 2030 to over 100% of total projected supply by 2035. With regard to copper, demand increases most significantly under the 'Net Zero by 2050' scenario between 2021 and 2025, with the proportion of supply increasing from 13.49% to 23.77%. However, after 2030, the 'Delayed Transition' scenario points towards potential disruptions and imbalances.

These findings also point towards potential price and financial stability implications, especially in the case of a sudden increase of demand after 2030, which could be associated with significant transition risks. Our findings on the total demand for TCMs and the demand shares of different technologies also offer insight on the type of potential disruption and bottlenecks that may occur. Disruptions or bottlenecks in the supply of materials will also have a substantial impact on the deployment of low-carbon technologies. This may delay the decarbonisation of the global economy and raise the potential for transition risks that jeopardise the realisation of a Paris-aligned transition.

In this context, further research is needed to investigate the possible transmission channels from TCM bottlenecks through the economy to the financial system with implications for price and financial stability, thereby implicating the mandate of central banks and financial supervisors. This initial exploratory assessment highlights the potential transition implications, and the need for further research on the material-specific contextualisation for challenges related to the reliable supply of TCMs, as well as to empirically assess the implications for the financial sector and the potential inflationary pressures. Further firm- and sector-level assessments will reveal potential positive and negative implications of the low-carbon transition, as well as winners and losers, thereby taking macroeconomic as well as mesoeconomic considerations into account.

Finally, the reorganisation of global value chains may have significant macroeconomic impacts on countries' trade and structure of balance of payments and will have to be subjected to further research (Volz, et al., 2021). Concerning the potential impact of the energy transition on TCM prices, further research could build on the findings of this paper and, in the context of the required unprecedented increase of TCM production, take additional factors into account (e.g., geopolitics) (Boer et al., 2021).

References

Adamas Intelligence. (2021a). *State of Charge: Evs, Batteries and Battery Materials H1.* Adamas Intelligence.

Adamas Intelligence. (2021b). *State of Charge: EVs, Batteries and Battery Materials H2.* Adamas Intelligence.

Andersson, B., & Jacobsson, S. (2000). Monitoring and assessing technology choice: the case of solar cells. *Energy Policy*, 1037-1049.

Anglo American. (2019). *Annual Report 2019.* Anglo American.

Anglo American. (2020). *Annual Report 2020.* Anglo American.

ANL. (2022). BatPac Model Software. Lemont, IL, USA.

Arderne, C., Zorn, C., Nicolas, C., & Koks, E. (2020). Preductive Mapping of the Global Power System using Open Data. *Science Data*.

Ashby, M. (2013). *Materials for low-carbon power.* Elsevier.

Attwood, J., & Sirtori-Cortina, D. (2021, May 18). Politics Are Turning Against Copper Mining in Top Producer Chile. Retrieved from Bloomberg: https://www.bloomberg.com/news/articles/2021-05-17/politics-are-turning-against-copper-mining-in-top-producer-chile?leadSource=uverify%20wall

Bödeker, J. M., Bauer, M., & Pehnt, M. (2010). *Aluminium and Renewable Energy Systems - Prospects for Sustainable Generation of Electricity and Heat.*

Baldi, L., Massimo, P., & Vandone, D. (2014). Clean Energy Industries and Rare Earth Materials: Economic and Financial Issues. *Energy Policy*, 53-61.

Ballinger, B., Stringer, M., Schmeda-Lopez, D., Kefford, B., Parkinson, B., Greig, C., & Smart, S. (2019). The vulnerability of electric vehicle deployment to critical mineral supply. *Applied Energy*.

Bank of England. (2022). *Results of the 2021 Climate Biennial Exploratory Scenario (CBES).* London: Bank of England.

Barteková, E. (2016). THE ROLE OF RARE EARTH SUPPLY RISK IN LOW-CARBON TECHNOLOGY INNOVATION. In W. F. Ismar Lima, *Rare Earths Industry* (pp. 153-170). Amsterdam: Elsevier.

Berry, C. (2014, 07 21). *Case study of a growth driver - silver us in solar.* Retrieved from PVTECH: https://www.pv-tech.org/case_study_of_a_growth_driver_silver_use_in_solar/

BHP. (2020). *Annual Report 2020.* BHP.

Blagoeva, D., Aves Dias, P., Marmier, A., & Pavel, C. (2016). *Assessment of potential bottlenecks along the materials supply chain for the future deployment of low-carbon* *energy and transport technologies in the EU.* Joint Research Centre of the European Union.

Bleiwas, D. (2010). *Byproduct Mineral Commodities Use for the Production of Photovoltaic Cells.* Reston: USGS Circular.

Bloomberg. (2022, September 22). The Rise of EVs and the Impact on Commodity Markets. Bloomberg.

Boer, L., Pescatori, A., & Stuermer, M. (2021, October). Energy Transition Metals. *IMF Working Paper*.

Burton, M., Farchy, J., & Cang, A. (2022, March 8). *LME Halts Nickel Trading After Unprecedented 250% Spike*. Retrieved from Bloomberg: https://www.bloomberg.com/news/articles/2022-03-08/lme-suspends-nickel-trading-after-unprecedented-price-spike#:~:text=The%20London%20Metal%20Exchange%20suspended%20trading%20in%20its,producer%20as%20well%20as%20a%20major%20Chinese%20bank

Calvo, G; Mudd, G; Valero, A; Valero, A. (2016). Decreasing Ore Grades in Global Metallic Mining: A Theoretical Issues or a Global Reality?. *Resources*

Carrara, S., Alves Dias, P., B., P., & Pavel, C. (2020). *Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system.* European Commission, Joint Research Centre. European Commission.

Church, C., & Crawford, A. (2018). *Green Conflict Minerals: The fuels of conflict in the transition to a low-carbon economy.* Winnipeg: International Institute for Sustainable Development.

Church, C., & Crawford, A. (2020). Minerals and Metals for the Energy Transition: Exploring the Conflict Implications for Mineral-Rich, Fragile States. In M. Hafner, & S. Tagliapietra, *The Geopolitics of the Global Energy Transition.* Springer Cham.

Committee on Earth Resources. (2008). *Minerals, Critical Minerals, and the U.S. Economy.* Washington D.C: National Research Council of National Academies.

Copper Alliance. (2022). *Global 2022 Semis End Use Data Set.* Retrieved from Copper Alliance: https://copperalliance.org/trends-and-data/market-intelligence/?fwp_resource_type_filter=data-set

Coulomb, R., Dietz, S., Godunova, M., & Bligaard Nielsen, T. (2015). Critical Minerals Today and in 2030: An analysis for OECD countries. *OECD Environment Directorate Working Paper Series*.

De Koning, A., Klijn, R., Huppes, G., Sprecher, B., & van Engelen, G. (2018). Metal supply constraints for a low-carbon economy? *Resources, Conservation & Recycling*, 202-208.

Deetman, S., de Boer, H., van Englenburg, M., van der Voet, E., & van Vuuren, D. (2021). Projected material requirements for the global electricity infrastructure - generation, transmission and storage. *Resources, Conservation & Recycling*.

Deetman, S., Paulink, S., van Vurren, D., van der Voet, E., & Tukker, P. (2018). Scenarios for Demand Growth of Metals in Electricity Generation Technologies, Cars, and Electronic Appliances. *Environmental Science & Technology*, 4950-4959.

Demirer, R., Ferrer, R., & Shahzad, S. (2020). Oil Price Shocks, Global Financial Markets and their Interconnectedness. *Energy Economics*.

Earl, T., Mathieu, L., Cornelis, S., Kenny, S., Ambel, C., & Nix, J. (2018). Analysis of long haul battery electric trucks in EU. *European Federation for Transport and Environment (T&E)*.

ECB. (2022). *Macro-financial scenarios for 2022 climate risk stress test.* Frankfurt: European Central Bank.

Elshkaki, A., & Graedel, T. (2013). Dynamic analysis of the global metals flows and stocks in electricity generation technologies. *Journal of Cleaner Production*, 260-273.

Elshkaki, A., Reck, B., & Graedel, T. (2017). Anthropogenic nickel supply, demand, and the associated energy and water use. *Resources, Conservation and Recycling*, 300-307.

ENCORE. (2022, 12 25). Retrieved from Encore Natural Capital Finance: https://encore.naturalcapital.finance/en/

Eurelectric. (2013). *Power Distribution in Europe - Facts & Figures.* Eurelectric.

European Commission. (2010). *Report of the Ad-hoc Working Group on defining critical raw materials.* European Commission.

European Commission. (2020a). *CRM List 2020*. Retrieved from JRC European Commission: https://rmis.jrc.ec.europa.eu/?page=crm-list-2020-e294f6

European Commission. (2020b). *Critical Raw Materials for Strategic Technologies and Sectors in the EU: A Foresight Study.* European Commission.

European Commission. (2020c). *Study on the EU's list of Critical Raw Materials - Final Report.*

EV Volumes. (2022). *EV Data Centre*. Retrieved from EV Volumes: https://www.ev-volumes.com/datacenter/

Falconer, I. (2009). Metals Required for the UK's Low Carbon Energy System: The case of copper usage in wind farms. *University of Exeter*.

Fishman, T., Myers, R., Rios, O., & Graedel, T. (2018). Implications of Emerging Vehicle Technologies on Rare Earth Supply and Demand in the United States. *Resources*.

Fizaine, F., & Court, V. (2015). Renewable electrcity producing technologies and metal depletion: A sensitivity analysis using EROI. *Ecological Economics*, 106-118.

Fthenakis, V. (2012). Sustainability metrics for extending thin-film photovoltaics to terawatt levels. *Energy & Water*, 425-430.

Gallego, C. (2021). The Role of Rare Earth Elements in the Deployment of Wind Energy in Colombia. *Boletín Geológico*.

García-Olivares, A., Ballabrera-Poy, J., García-Ladona, E., & Turiel, A. (2012). A global renewable mix with proven technologies and common materials. *Energy Policy*, 561-574.

Gielen, D. (2021). *Critical Materials for the Energy Transition.* Abu Dhabi: International Renewable Energy Agency (IRENA).

Gielen, D., & Lyons, M. (2022). *Critical Materials for the Energy Transition: Lithium.* International Renewable Energy Agency (IRENA).

Giurco, D., Dominish, E., Florin, N., Watari, T., & McLellan, B. (2019). Requirements for Minerals and Metals for 100% Renewable Scenarios. In S. Teske, *Achieving the Paris Climate Agreement Goals* (pp. 437-457). Springer.

Global Transmission. (2022). *Global Transmission Report.* Retrieved from Global Transmission Info: htps://globaltransmission.info

Global Witness. (2014). *Conflict.* Global Witness.

Goonan, T. (2012). *Lithium Use in Batteries.* U.S. Geological Survey.

Government of Canada. (2021). *Critical Minerals*. Retrieved July 2022, from https://www.nrcan.gc.ca/our-natural-resources/minerals-mining/critical-minerals/23414

Grantham, J. (2018). The Race of Our Lives Revisited. Retrieved from Morningstar: jg_morningstar_race-of-our-lives_8-18.pdf (gmo.com)

Gruber, P., Medina, P., Keoleian, G., Kesler, S., Everson, M., & Wallington, T. (2011). Global Lithium Availability: A Constraint for Electric Vehicles? *Journal of Industrial Ecology*.

Guezuraga, B., Zauner, R., & Pölz, W. (2012). Life cycle assessment of two different 2 MV class wind turbines. *Renewable Energy*, 37-44.

Habib, K., & Wenzel, H. (2014). Exploring rare earth supply constraints for the emerging clean energy technologies and the role of recycling. *Journal of Cleaner Production*, 348-349.

Habib, K., & Wenzel, H. (2016). Reviewing resource criticality assessment from a dynamic and technology specific perspective - using the case of direct-drive wind turbines. *Journal of Cleaner Production*, 3852-3863.

Harper, G., Sommerville, R., Kendrick, E., Driscoll, L., Slater, P., Stolkin, R., . . . Anderson, P. (2019). Recycling lithium-ion batteries from electric vehicles. *Nature*.

Harrison, G., Maclean, E., Karamanlis, S., & Ochoa, L. (2010). Life Cycle Assessment of the Transmission Network in Great Britain. *Energy Policy*.

Heijlen, W., Franceschi, G., Duhayon, C., & Van Nijen, K. (2021). Assessing the adequacy of the global land-based mine development pipeline in the light of future high-demand scenarios: The case of the battery-metals nickel (Ni) and cobalt (Co). *Resources Policy*.

Helbig, C., Bradshaw, A., Wietschel, L., Thorenz, A., & Tuma, A. (2018). Supply risks associated with lithium-ion battery materials. *Journal of Cleaner Production*, 274-286.

Hoenderdaal, S., Espinoza, L., Marschieder-Weidemann, F., & Graus, W. (2013). Can a dysprosium shortage threaten green energy technologies? *Energy*, 344-355.

Hund, K., La Porta, D., Fabregas, T., Laing, T., & Drexhange, T. (2020). *Minerals for Climate Action: The Mineral Intensity for the Clean Energy Transition.* Washington: The World Bank.

IEA. (2020). Energy Technology Perspectives 2020 Dataset. Paris.

IEA. (2021a). *The Role of Critical Minerals in Clean Energy Transitions.* Paris: International Energy Agency.

IEA. (2021b). *Renewables 2021 - Analysis and forecast to 2026.* Paris: International Energy Agency.

IPCC. (2022). *Summary for Policymakers: Climate Change 2022: Mitigation of Climate Change.* Cambridge, UK and New York, USA: IPCC.

IRENA. (2017). *Renewable energy benefits: Leveraging local capacity for solar PV.* Abu Dhabi: International Renewable Energy Agency.

Jensen, F., & Asmarini, W. (2015, December 4). *UPDATE 2-Freeport Indonesia head says speaker of parliament tried to extort shares*. Retrieved from Reuters: https://www.reuters.com/article/indonesia-freeport-probe-idlNL3N13T1WX20151204

Kalantzakos, S. (2018). *China and the Geopolitics of Rare Earths.* Oxford: Oxford University Press.

Kavlak, G., McNerney, J., Jaffe, R., & Trancik, J. (2015). Metal production requirements for rapid photovoltaics deployment. *Energy & Environmental Science*.

Kimani, A. (2022, March 21). *Lithium Prices Have Nearly Doubled In 2022 Amid Insane Commodity Rally*. Retrieved from Oil Price: https://oilprice.com/Energy/Energy-General/Lithium-Prices-Have-Nearly-Doubled-In-2022-Amid-Insane-Commodity-Rally.html

Kleijn, R., & van der Voet, E. (2010). Resource constraints in a hydrogen economy based on renewble energy sources: An exploration. *Renewable and Sustainable Energy Reviews*, 2784-2795.

Lacal-Arántegui, R. (2015). Materials use in electricity generators in wind turbines - state-of-the-art and future specifications. *Journal of Cleaner Production*, 275-283.

Landau, B., & Skudelny, F. (2009). Pass-Through of External Shocks Alogn the Pricing Chain: A Panel Estimation Appraoch for the Euro Area. *ECB Working Paper Series*.

Le, T., & Chang, Y. (2015). Effects of oil price shocks on the stock market performance: Do nature of shocks and economics matter. *Energy Economics*.

Levin, M. (2022). *The Nickel Market has Gone Bonkers.* Retrieved from Marketplace: https://www.marketplace.org/2022/03/21/the-nickel-market-has-gone-bonkers/

Maguwu, F. (2017). *Investigating Illicit Financial Flows in Zimbabwe's Lithium Mining Sector.* Trust Africa.

Månberger, A., & Stenqvist, B. (2018). Global metal flows in the renewable energy transition: Exploring the effects of substitutes, technological mix and development. *Energy Policy*, 226-241.

Martínez, E., Sanz, F., Pellegrini, S., Jiménez, E., & Blanco, J. (2009). Life cycle assessment of a multi-megawatt wind turbine. *Renewable Energy*.

Mazalto, M. (2009). GOVERNANCE, HUMAN RIGHTS AND MINING IN THE DEMOCRATIC REPUBLIC OF CONGO. In B. Campbell, *Mining in Africa.* Pluto Press.

McKinsey. (2022). *The net-zero transition: What it would cost, what it could bring.* McKinsey & Company Global Institute.

McLellan, B., Yamasue, E., Tezuka, T., Corder, G., & Golev, A. (2016). Critical Minerals and Energy-Impacts and Limitations of Moving to Unconventional Resources. *Resources*.

Menon, R. (2022). Navigating Policies During Times of Great Uncertainties. *IMF Annual Meeting.* Washington: International Mmonetary Fund.

Michaels, K., Maréchal, L., & Katz, B. (2022, 09 09). *Why is ESG so important to critical mineral supplies, and what can we do about it?* Retrieved from International Energy Agency: https://www.iea.org/commentaries/why-is-esg-so-important-to-critical-mineral-supplies-and-what-can-we-do-about-it

Moody's Analytics. (2022). *Economic Forecast Scenarios: Climate Risk*. Retrieved from Moody's Analytics: https://www.moodysanalytics.com/product-list/climate-risk-scenarios

Moreau, V., Reis, P., & Vuille, F. (2019). Enough Metals? Resource Constraints to Supply a Fully Renewable Energy System. *Resources*.

Moss, R., Tzimas, E., Kara, H., Willis, P., & Kooroshy, J. (2013a). The potential risks from metals bottlenecks to the deployment of Strategic Energy Technologies. *Energy Policy*, 556-564.

Moss, R., Tzimas, E., Willis, P., Arendor, J., Espinoza, L., & al., e. (2013b). *Critical Metals in the Path towards the Decarbonisation of the EU Energy Sector: Assessing Rare*

Metals as Supply-Chain Bottlenecks in Low-Carbon Energy Technologies. Petten: Joint Research Centre of the European Union.

Nassar, N., & Fortier, S. (2021). *Methodology and Technical Input for the 2021 Review and Revision of the U.S. Critical Minerals List.* U.S. Geological Survey.

NGFS. (2022). *Scenarios Portal*. Retrieved from Network for Greening the Financial System: https://www.ngfs.net/ngfs-scenarios-portal/

NGFS-INSPIRE. (2022). *Central Banking and Supervision in the Biosphere.* NGFS.

Noerochim, L., Suwarno, S., Idris, N., & Dipojono, H. (2021). Recent Development of Nickel-Rick and Cobalt-Free Cathode Materials for Lithium-Ion Batteries. *Batteries*.

Northey, S., Mudd, G., Werner, T., Jowitt, S., Haque, N., Yellishetty, M., & Weng, Z. (2017). The exposure of global base metal resources to water criticality, scarcity and climate change. *Global Environmental Change*, 109-124.

Nuklu, C., Casas, L., Haufroid, V., & et al., e. (2018). Sustainability of artisanal mining of cobalt in DR Congo. *Nature Sustainability*, 495-504.

Olivetti, E., Ceder, G., Gaustad, G., & Xinkai, F. (2017). Lithium-Ion Battery Supply Chain Considerations: Analysis of Potential Bottlenecks in Critical Minerals. *Joule*, 229-243.

O'Sullivan, M., Overland, I., & Sandalow, D. (2017). *The Geopolitics of Renewable Energy.* New York: Center on Global Energy Policy at Columbia University.

Pihl, E., Kushnir, D., Sandén, B., & Johnsson, F. (2012). Material constraints for concentrating solar thermal power. *Energy*, 944-954.

Pitron, G. (2020). *The Rare Metals War: The Dark Side of Clean Energy and Digital Technologies.* Scribe Publications Pty Limited.

Prause, L. (2020). Conflicts related to resources: The cases of cobalt mining the Democratic Republic of Congo. In A. Bleicher, & A. Pehlken, *The Material Basis of Energy Transitions.* Elsevier.

Rüttinger, L., van Ackern, P., Lepold, T., Vogt, R., & Auberger, A. (2020). Impacts of climate change on mining, related environmental risks and raw material supply. *Umweltbundesamt*.

Ramussen, K., Wenzel, H., Bangs, C., Petavratzi, E., & Liu, G. (2019). Platinum Demand and Potential Bottlenecks in the Global Green Transition: A Dynamic Material Flow Analysis. *Environmental Science Technology*.

Roache, S., & Erbil, N. (2011). How Commodity Price Curves and Inventories React to a Short-Run Scarity Shock. *IMF Working Paper*.

Roelich, K., Dawson, D., Purnell, P., Knoeri, C., Revell, R., Busch, J., & Steinberger, J. (2014). Assessing the dynamic material criticality of infrastructure transitions: A case of low carbon electricity. *Applied Energy*, 378-386.

S&P Global. (2022a). *Climate Credit Analytics*. Retrieved from S&P Global Market Intelligence: https://www.spglobal.com/marketintelligence/en/solutions/climate-credit-analytics

S&P Global. (2022b). S&P Global Capital IQ Pro.

Sadorsky, P. (1999). Oil Price Shocks and Stock Market Activity. *Energy Economics*.

Saishree, I., & Padhi, P. (2022). Exploring the dynamics of the equity-commodity nexus: A study of base metal futures. *The Journal of Futures Markets*.

Schnabel, I. (2022). A new age of energy inflation: climateflation, fossilflation and green flation. *ECB XXII Conference.* European Central Bank.

Schodde, R. (2014). Key issues affecting the time delay between discovery and development - is it getting harder and longer? MinEx Consulting.

Schodde, R. (2017). Long term trends in global exploration - are we finding enough metal? *Fennoscandian Exploration and Mining Conference.* MineEx Consulting.

Schodde, R. (2019). Trends in exploration. *International Mining and Resource Conference (IMARC).* MineEx Consulting.

SEMI. (2014). *International Technology Roadmap for Photovoltaic, Fifth Edition.*

Semieniuk, G., Campiglio, E., Mercure, J.-F., Volz, U., & Edwards, N. (2020, August 3). Low-carbon transition risks for finance. *Advanced Review*.

Seneca Group. (2014). *Major Infrastructure Projects in Mexico - A Resource Guide for the U.S Industry.* Washington: Seneca Group.

Sergeant, A., van Straaten, M., & Rats, M. (2022). *Copper, Aluminium and the Energy Transition.* Morgan Stanley.

Shamsher, S. (2021). Financialisation of commodities - Empirical evidence from the Indian financial market. *IIMB Management Review*, 38-49.

Sonter, L., Ali, S., & Watson, J. (2018). Mining and biodiversity: key issues and research needs in conservation science. *The Royal Society Publishing*.

Stamp, A., Wäger, P., & Hellweg, S. (2014). Linking energy scenarios with metal demand modeling - The case indium in CIGS solar cells. *Resources, Conservation and Recycling*, 156-167.

Teer, J., & Bertolini. (2022). *Reaching breaking point: The semiconductor and critical raw material ecosystem at a time of great power rivalry.* Hague: The Hague Centre for Strategic Studies.

Teske, S., Florin, N., Dominish, E., & Giurco, D. (2016). *RENEWABLE ENERGY AND DEEP-SEA MINING: SUPPLY, DEMAND AND SCENARIOS.* Institute for Sustainable Futures.

Tsamis, A. S. (2015). *Recovery of Rare Earths from Electronic Wastes: An Opportunity for High-Tech SMEs.* European Parliamentary Research Service.

Turconi, R., Simonsen, C., Byriel, B., & Astrup, T. (2014). Life Cycle Assessment of the Danish Electricity Distribution Network. *International Jounral Life Cycle Assessment*, 100-108.

U.S. Department of Energy. (2011). *Critical Minerals Strategy: 2011.* U.S. Department of Energy.

UNEP. (2011). *Recycling Rates of Metals - A Status Report.* UNEP.

University of Washington. (2022). *What is a lithium-ion battery and how does it work?* Retrieved from Clean Energy Institute: https://www.cei.washington.edu/education/science-of-solar/battery-technology/

Upadhyay, A., Laing, T., Kumar, V., & Dora, M. (2021). Exploring barriers and drivers to the implementation of circular economy practices in the mining industry. *Resources Policy*.

USGS. (2021). *Mineral Commodities Summaries.* U.S Geological Survey.

USGS. (2022). *Mineral Commodity Summaries 2022.* U.S. Department of the Interior.

USGS. (2022a). *2022 Final List of Critical Minerals.* U.S. Geological Survey & Department of the Interior.

USGS. (2022b). *Mineral Commodities Summaries.* U.S. Geological Survey.

Valero, A., Valero, A., Calvo, G., & Ortego, A. (2018). Material bottlenecks in the future development of green technologies. *Renewable and Sustainable Energy Reviews*, 178-200.

Valero, A., Valero, A., Guiomar, C., Ortego, A., Ascaso, S., & Palacios, J.-L. (2018). Global material requirements for the energy transition. An exergy flow analysis of decarbonisation pathways. *Energy*, 1174-1184.

Vestas. (2006). *Life Cycle Assessment of Offshore and Onshore Sited Wind Power Plants Based on Vestas V90-3.0MV Turbines.*

Vidal, O., Goffé, B., & Arndt, N. (2013). Metals for a low-carbon society. *Nature Geoscience*, 894-896.

Volz, U., Campiglio, E., Espagne, E., Mercure, J.-F., Oman, W., Pollitt, H., . . . Svartzman, R. (2021). *Transboundary Climate-related Risks: Analysing the Impacts of a Decarbonisation of the Global Economy on International Trade, Finance, and Money.* IMF Statistical Forum.

Warren Centre. (2016). *THE COPPER TECHNOLOGY ROADMAP 2030: Asia's growing appetite for copper.*

Watari, T., McLellan, B., Giurco, D., Dominish, E., Yamasue, E., & Nansai, K. (2019). Total material requirement for the global energy transition to 2050: A focus on transport and electricity. *Resources, Conservation & Recycling*, 91-103.

Wilburn, D. (2011). *Wind Energy in the United States and Materials Required for the Land-Based Wind Turbine Industry From 2010 Through 2030.* U.S. Geological Survey Scientific Investigations Report.

Woodhouse, M., Goodrich, A., Margolis, R., James, T., Lokanc, M., & Eggert, R. (2013). *Supply-Chain Dynamics of Tellurium, Indium, Manufacturing Costs.*

World Bank. (2016). *SPECIAL FOCUS - From Commodity Discovery to Production Vulnerability and Policies in LICs.* Washington: The World Bank.

World Bank Group. (2017). *The Growing Role of Minerals and Metals for a Low Carbon Future.* Washington: World Bank Group.

WRI. (2022). *Water Risk Atlas Aqueduct*. Retrieved from World Resource Institute: https://www.wri.org/data/aqueduct-water-risk-atlas

Zimmermann, T., Rehberger, M., & GöBling-Reisemann, S. (2013). Material Flows Resulting from Large Scale Deployment of Wind Energy in Germany. *Resources*, 303-334.

Appendix 1 – Literature Review of Material Requirements for Energy Generation Technologies

(Ashby, 2013)	Wind Power Material Intensity Literature Review
(Barteková, 2016)	
(Bödeker, Bauer, & Pehnt, 2010)	
(Carrara S. , Alves Dias, B., & Pavel, 2020)	
(Elshkaki & Graedel, 2013)	
(Falconer, 2009)	
(García-Olivares, Ballabrera-Poy, García-Ladona, & Turiel, 2012)	
(Guezuraga, Zauner, & Pölz, 2012)	
(Habib & Wenzel, 2016)	
(Habib & Wenzel, 2014)	
(Hoenderdaal, Espinoza, Marschieder-Weidemann, & Graus, 2013)	
(IEA, 2021a)	
(Kleijn & van der Voet, 2010)	
(Lacal-Arántegui, 2015)	
(Månberger & Stenqvist, 2018)	
(Martínez, Sanz, Pellegrini, Jiménez, & Blanco, 2009)	
(McLellan, Yamasue, Tezuka, Corder, & Golev, 2016)	
(Moss, Tzimas, Kara, Willis, & Kooroshy, 2013)	
(Roelich, et al., 2014)	
(Teske, Florin, Dominish, & Giurco, 2016)	
(U.S. Department of Energy, 2011)	
(Vestas, 2006)	
(Wilburn, 2011)	
(World Bank Group, 2017)	
(Zimmermann, Rehberger, & GöBling-Reisemann, 2013)	

(Andersson & Jacobsson, 2000)	Photovoltaic Solar Power Material Intensity Literature Review
(Ashby, 2013)	
(Berry, 2014)	
(Bleiwas, 2010)	
(Carrara S. , Alves Dias, B., & Pavel, 2020)	
(Elshkaki & Graedel, 2013)	
(Fizaine & Court, 2015)	
(Fthenakis, 2012)	
(Giurco, Dominish, Florin, Watari, & McLellan, 2019)	
(IEA, 2021a)	
(IRENA, 2017)	
(Kavlak, McNerney, Jaffe, & Trancik, 2015)	

(McLellan, Yamasue, Tezuka, Corder, & Golev, 2016)	
(Moss, Tzimas, Kara, Willis, & Kooroshy, 2013)	
(SEMI, 2014)	
(Stamp, Wäger, & Hellweg, 2014)	
(Teske, Florin, Dominish, & Giurco, 2016)	
(U.S. Department of Energy, 2011)	
(Valero, Valero, Calvo, & Ortego, 2018)	
(Warren Centre, 2016)	
(Woodhouse, et al., 2013)	
(World Bank Group, 2017)	

(Ashby, 2013)	Concentrated Solar Power Material Intensity Literature Review
(Bödeker, Bauer, & Pehnt, 2010)	
(IEA, 2021a)	
(Moss, Tzimas, Kara, Willis, & Kooroshy, 2013)	
(Moss, et al., 2013)	
(Pihl, Kushnir, Sandén, & Johnsson, 2012)	
(Teske, Florin, Dominish, & Giurco, 2016)	
(World Bank Group, 2017)	

(Ashby, 2013)	Hydropower Material Intensity Literature Review
(IEA, 2021a)	
(Moss, Tzimas, Kara, Willis, & Kooroshy, 2013)	

(Ashby, 2013)	Geothermal Material Intensity Literature Review
(IEA, 2021a)	
(Moss, Tzimas, Kara, Willis, & Kooroshy, 2013)	
(Watari T. , et al., 2019)	

(Ashby, 2013)	Biomass Material Intensity Literature Review
(IEA, 2021a)	
(Moss, et al., 2013)	

(Ashby, 2013)	Nuclear Material Intensity Literature Review
(Fizaine & Court, 2015)	
(IEA, 2021a)	
(Moss, et al., 2013)	
(Valero, et al., 2018)	

(Moss, Tzimas, Kara, Willis, & Kooroshy, 2013)	Carbon Capture and Storage Material Intensity Literature Review
(World Bank Group, 2017)	

(Vidal, Goffé, & Arndt, 2013)	Oil, Coal & Natural Gas Material Intensity Literature Review

Appendix 2 – Case Study Analysis for Lithium, Nickel and Copper

Lithium

Lithium is mainly used in EV batteries, but also in freight and battery storage. Lithium-ion batteries are used in many other products such as wireless communication, mobile computing, and power tools (Goonan, 2012). Moreover, about 25% of lithium minerals are used for products others than batteries, primarily in the ceramics and glass sector (USGS, 2022b). Some substitutes to lithium compound exist for batteries. Examples for primary batteries are calcium, magnesium, mercury, and zinc as anode material (Ibid). However, these substitutes need to be considered against the technical requirements for EV deployment, in particular the trade-off between energy density, thermal stability and life-cycle use (University of Washington, 2022).

In our assessment, the demand for lithium is approximately 210K tonnes by 2025 under a net-zero scenario, approximately 247% of total production in 2019 (about 85K tonnes) (USGS, 2021). However, the demand rapidly increases and is expected to reach an annual average of 634K tonnes for the 2031-2035 period. In 2021, lithium carbonate equivalent (LCE) was estimated to be 494,268 tonnes (S&P Global, 2022b), and an estimated 172,900 tonnes were deployed in the EV market (Adamas Intelligence, 2021a; 2021b). Consequently, approximately 35% of total LCE supply was directly deployed into the EV market in 2021. This large market share for lithium production makes lithium more price sensitive to demand shocks from EVs and energy storage additions, due to lack of market displacement available. At the start of 2022 the market has experienced significant increases in LCE prices, with 300-500% increases year-to-date, which continue to persist (S&P Global, 2022b). Some analysis suggests the expected deployment of EVs will maintain market tightness, with higher LCE prices, in the short term (Gielen & Lyons, 2022; Bloomberg, 2022).

Moreover, lithium is exposed to various supply-side risks. As indicated by USGS data, the known reserves and the production of lithium are relatively highly concentrated both in terms of geographic region and market concentration (USGS, 2021; Gielen & Lyons, 2022). Hence, supply-side risks may have substantial impacts in the future. While substitutions in battery chemistries may mitigate demand-driven costs, previous research suggests that different chemistries are all exposed to significant supply-side risks, except for LFP-LTO, limiting the effectiveness of substitution (Helbig et al., 2018). Furthermore, the end-of-life (EOL) recycling rates of lithium are currently low, at about 10% (Månberger & Stenqvist, 2018). The flammable electrolyte in lithium-ion batteries makes it difficult to increase recycling due to its dangerous nature (Harper et al., 2019). Therefore, lithium demand will need to be met predominantly through primary supply, at least in the near-term.

However, the total production of LCE has increased by 140% between 2011 and 2020, with a particularly fast increase since 2016 (USGS, 2013, 2021). This is likely due to the relatively short mine development lead times for lithium mines, which is between 4 and 7 years (Schodde, 2017), well below the average of 16.9 years for critical minerals (IEA, 2021a). Therefore, primary production can be upscaled much more quickly, which is reflected in the estimated future production, where 15% of global production will come from new mines by 2025 (S&P Global, 2022b). This may alleviate the demand-side pressures of lithium in the medium-term as mining companies will be able to be more agile to an increase in demand. However, there are further complexities that need to be considered, including the chemistry type, which determines the type of lithium compound that is most suitable, either lithium hydroxide or lithium carbonate (Gielen & Lyons, 2022). Therefore, market tightness may arise through demand for a specific lithium compound, depending on battery chemistry.

Nickel

From our mineral intensity estimates, we observe nickel is used throughout energy generation technologies, except for PV solar, but also in energy storage and the dominant sub-technologies for EVs batteries (where it provides a cathode material for lithium-ion batteries). Furthermore, in recent years, EV manufacturers have switched to battery chemistries with a higher nickel content to reduce their requirement for cobalt, due to the ethical implications within its supply chain (Adamas Intelligence, 2021a); IEA, 2021a). This reflects the potential broad impact across low-carbon technological deployment under a scenario where there are sharp increases in the price of nickel, or price volatility resulting from the materialising of supply-related risks.

Supply risks related to the geographical concentration of production are relatively lower for nickel than for other minerals. Indonesia produced 33% of the world's total primary supply in 2019, followed by Philippines (12%), Russia (11%), New Caledonia (8%), Canada (7%) and China (5%) (USGS, 2022b). Furthermore, recycling rates of nickel are relatively high at about 60% (Månberger & Stenqvist, 2018); UNEP, 2011). Additionally, the wide variety of end-uses for nickel, due to its use as an alloy for steel, means the historical production of nickel is relatively high. Hence, a substantial proportion of future demand can be met through secondary supply, i.e., recycling, which can be seen in the Figure 7. Recent increases in production are mainly driven by Indonesia, which has increased production by almost 30% between 2020 and 2021 (USGS, 2022b), leading to a further concentration of global supply, which may increase supply risk factors over the longer term.

The project lead development time between discovery and commencing operation is substantial, between 13 and 19 years according to (Schodde, 2017) and 12 years according to Heijlen et al, 2021, and existing conversion rates are relatively low, at 35% (Schodde, 2017). Therefore, the price elasticity of supply is inelastic in the short-term due to substantial constraints. Additionally, the supply of nickel also competes with other uses such as stainless steel. If the rate of demand increase for nickel greatly outstrips the rate of annual production increases, there is a possibility of sharp price increases. Furthermore, the total growth demand for nickel depends on other sectors (same as copper), compared to more niche metals, such as lithium (Gielen, 2021).

The price of nickel has been extremely volatile in recent years and exacerbated following the recent sanctions on Russia (Burton et al., 2022). The London Metal Exchange responded by ceasing trading of nickel (Ibid). If nickel prices are to remain high, several patterns may emerge, including the reduction of nickel within low-carbon technologies. For instance, Tesla responded to rising prices by switching some EV models to less efficient batteries that do not use nickel (Levin, 2022). In 2021, the main battery chemistry deployed in EVs was LFP, which does not contain nickel (Adamas Intelligence, 2021b), which may indicate a reduction in nickel use for EVs in coming years. While reliance on nickel might be reduce for EV deployment, LFP chemistries require higher amounts of copper and graphite, which may exacerbate pressures of these supply chains. Moreover, these alternatives offer inferior performance (Gielen, 2021), which may reduce their uptake and maintain the demand pressures on nickel.

Copper

While there is ample production to meet current demand from low-carbon technologies, copper is used extensively in other sectors, including construction, manufacturing and industrial applications (Copper Alliance, 2022). Hence, even small increases in annual demand may have a broad economic impact. Moreover, copper lead development times on new mines average 16.4 years (Schodde, 2017), hindering the ability to upscale production quickly in response to demand. Hence, in the near term, the elasticity of supply to a change in price is limited. Therefore, rapid demand increases may lead to a price squeeze in the short-term. Evidence of market tightness is already apparent with the current copper prices reaching 10-year highs (S&P Global, 2022b). Current analysis indicates such tightness may well continue for much of the decade, with the deployment of low-carbon technologies constituting a substantial factor (Sergeant et al., 2022). For example, copper demand in EVs is estimated to grow at 20% CAGR (Ibid).

Meanwhile, in 2015, worldwide identified copper resources were of 2.1 billion tonnes, and undiscovered resources were estimated at about 3.5 billion tonnes (USGS, 2021), thereby largely covering demand. Moreover, recycling rates for copper are particularly high, at around 60% (Månberger & Stenqvist, 2018); UNEP, 2011). Therefore, short-term, demand-induced price increases are likely to be eased by expansions in production over a greater time horizon.

Current production of copper is relative dispersed, with 28% in Chile and 12% in Peru, followed by China (8%), DRC (6%), the US (6%) and Australia (5%) (USGS, 2022b). However, there are two key factors that may affect the future supply for copper, namely grade of mineral ore and climate risk. Declining ore quality in Chile and Peru has been well-documented (Calvo et al., 2016), and the reduction in conversion rates for copper projects reflects this (Schodde, 2017). The price of copper may need to rise further to make new projects economically viable, which will raise the material cost for low-carbon technologies. Most copper production projects are currently located in water-stressed regions WRI, 2022 (Rüttinger et al., 2020). Diversified mining companies, which are the primary producers of copper, are already frequently reporting weather-related events as a reason for reduced production within their annual financial reports (BHP, 2020, Anglo American, 2020). As shown extensively within the academic literature, the physical impacts of climate change are non-linear in nature, which translate to a non-linear risk to the reliable supply of copper. This exposes copper to sudden and substantial changes in production, which may translate into price volatility.

While grade quality and climate risk may pose the greatest supply-related risks, we cannot ignore the social risks relating to mining. For example, the recently elected Chilean government has promised to reduce to economy's dependence on mining exports, in part due to local resistance to mining activities (Attwood & Sirtori-Cortina, 2021). This may lead to reduced production in the country with the largest current production capacity and economically available reserves (USGS, 2022b). Therefore, the main risk from copper is not whether demand can be met over the long-term, but consistently met year-on-year to enable the scale-up of low-carbon technologies given the potential risks in its supply chain.

Appendix 3 – Additional Analysis of TCMs

This Appendix explores the technology-specific demand for the focus TCM materials between the period 2021 to 2040.

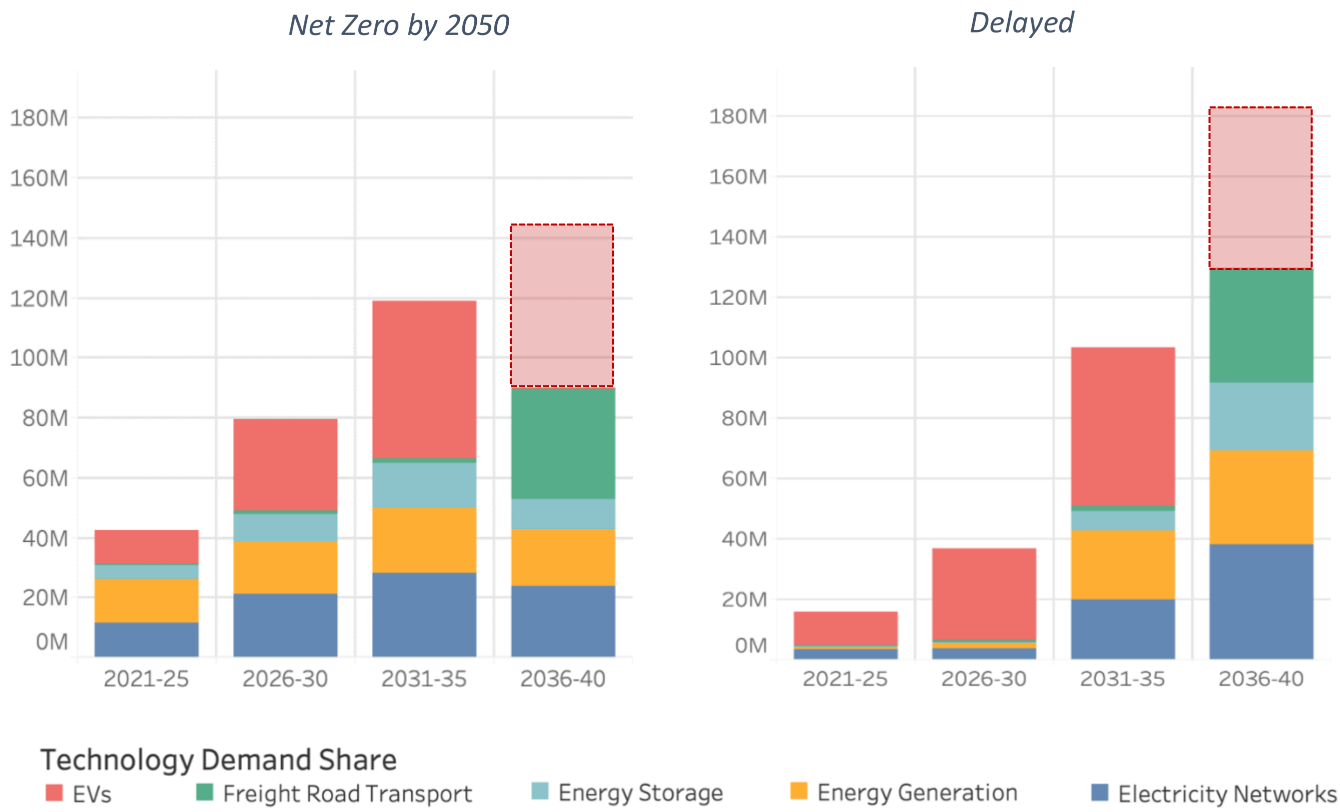
The TCM demand share of different transition technologies

For the analysis of the TCM demand share of different transition technologies, the 5-year average demand is taken for each time-period, which negates the scenario manipulation through interpolation, seen in the analysis 5.2. We observe the estimated demand share by technology type, divided into energy generation, energy storage, road freight transportation and EVs. Because some material demand is shared between different technology types, the analysis enables the examination of potential demand-induced ‘bottlenecks’ from cross-technology deployment and the implications for the transition. Moreover, when there is a significant increase in a specific technology-type between periods, the implication for technology-specific materials can be identified. *Figure 4* highlights these differences in TCM demand by displaying the demand shares of the different technologies, comparing the ‘Net Zero by 2050’ and the 'Delayed Transition’ scenario for 2021 to 2040. For the final time-period, we extend material demand for EVs from 2035 to illustrate the potential total mineral demand *(illustrated by the shaded area*).

For the ‘Net Zero by 2050’ scenario, the first interval (2021 and 2025) material demand is primarily driven from energy generation technologies, which account for 34% of demand for the focus minerals (14.6Mt). Material demand from other technologies, especially EVs and road freight technologies, increases at a greater rate in subsequent 5-year intervals. The most prominent demand shift occurs between the 2031-35 and 2036-40 intervals, when demand for freight technologies increases 1.8Mt to 37.4Mt. The absolute storage demand for TCMs increases in absolute terms from 2021-25 to 2031-35 from 4.9Mt to 14.8Mt, before falling to 10.1Mt in the period 2036-40. Finally, the material demand for electrical networks directly correlate to the deployment of energy generation technologies, with demand increasing for the first three periods, before falling between 2036-40. The limited availability of materials suitable for electrical transmission networks increases the probability of substantial demand-induced pressures on copper, which may translate to higher prices.

The rapid increase in demand for freight technologies between 2036-40 poses different risks. These technologies share the demand for the same minerals as energy storage technologies, particularly for vanadium, which is integral for vanadium redox flow batteries (VRFB) used in freight transportation and energy storage technologies, where energy density is not as important (IEA, 2021a). Therefore, demand-induced shortages in select minerals may reduce the deployment of energy storage technologies, and expose the global economy to greater energy intermittency, inherent within current energy generation technologies. This intermittency may have implications for energy prices and cause similar economic disruption as that of the current energy crisis.

Figure 4: Mineral Demand by Technology



In the 'Delayed Transition' scenario, demand for focus materials is initially be driven by EV technologies. While this is a likely result of our model augmentation through external, more precise EV data that does not necessarily reflect the scenario narrative, it offers interesting insights. Hence, for the first two time periods, EVs represent approximately 70% (11.1Mt, 2021-2025) and 83% (30.4Mt, 2026-2030) of demand. Furthermore, the results reveal a dramatic demand increase from the other technologies in the third and fourth intervals. Between 2026-30 and 2031-35, material demand from energy generation, electrical network and storage technologies significantly increase as a proportion of total material demand, from 2.0Mt, 3.7Mt, and 0t, to 22.6Mt, 19.9Mt, and 6.8Mt, respectively. Material demand from freight vehicles remains relatively limited in all periods except 2036-40, where minerals demand significantly increases from 1.7Mt to 37.9Mt. These findings underscore the effect of a late but sudden scenario on mineral demand, and the potential bottleneck pressure which may be induced from a stark increase in the rate of annual demand increases.

The demand for individual TCMs for the NGFS 'Net Zero by 2050' and 'Delayed Transition' Scenarios

In order to estimate the demand growth for eight of the focus TCMs over 5-year intervals between 2021 and 2040 (vanadium is excluded from the analysis because accurate 2020 demand figures could not be collected), relative demand is examined, focusing on instances where demand from low-carbon technologies for each focus material is indexed to material demand from 2020 (demand in 2020 equals zero). Numbers for 2020 demand are taken from the International Energy Agency (IEA) website. The analysis investigates the demand rate increases for specific minerals in each of the 5-year periods under the two scenarios (NZ and DS, see *Figure 5* below). The average demand per material within each 5-year period is taken to represent the rate of demand increase. Within both scenarios, demand for all focus materials increases between each 5-year period from 2021 to 2040[10]. For both scenarios, we assume EV deployment is maintained between 2036-2040 with deployment in 2035, the same assumption as used in the analysis in this paper.

Under the 'Net Zero by 2050' scenario for 2021-25, indexed demand for most materials increases at least 5-fold compared to 2020 baseline demand, except for nickel, cobalt and REEs, which increase approximately by 4.1, 4.9, and 3.0 times, respectively. The greatest demand growth is seen in copper and molybdenum, with an indexed growth rate of 7.3 and 8.8, respectively. In the 2026-30 period, we find graphite, lithium, cobalt and copper to be subject to demand increases of over 11 times compared to the 2020 baseline, with demand for graphite almost reaching 17 times the base. This is primarily driven by the rapid uptake in EVs caused by our scenario extension. However, the deployment of energy storage as well as freight technologies also contribute towards the demand for these materials.

For the period 2036-40, material demand increases by 37.4 and 51.6 times for two focus minerals (graphite and lithium, respectively) and over 12 times for all materials. Lithium demand increases indicate substantial demand-induced pressures that could also manifest for graphite, cobalt, manganese, copper and nickel. Graphite and lithium are exclusively used in batteries, and supply disruptions could significantly affect capabilities to increase energy storage and transportation technologies. Copper, manganese and nickel are also extensively used in energy generation technologies, including wind, hydro, geothermal and nuclear, as well as in batteries. Disruptions of the supply chains of these materials could also have greater implications for clean technology companies, as well as for the broader realisation for the transition.

Under the 'Delayed Transition' scenario, the first period displays minimal demand increases, with none of the materials experiencing demand growth greater than 4 times. This is despite the inclusion of the EVs extension data. In fact, material demand for molybdenum averages slightly below 2020 demand, by -0.05. This reflects the narrative of the 'Delayed Transition' scenario, which includes minimal capacity additions for energy generation and storage technologies prior to 2030.

[10] Except for molybdenum under the 'Delayed Transition' scenario in the 2040 period. This is because annual capacity additions fall for electricity generation technologies requiring molybdenum in the period 2036-40, compared with 2031-35.

By 2030, both lithium and graphite experience over a 10-fold demand increase compared to the 2020 baseline, primarily driven by the inclusion of EVs. However, indexed demand growth for materials not primarily used in EVs remain low, with the demand for copper, molybdenum, nickel and REEs all below 6 times the 2020 baseline. In the period 2031-35, we find substantial increases in indexed demand for all focus minerals. Molybdenum, copper and REEs experience steep demand increases from a low baseline in the previous time-period (2026-30), with increases from 0.5 to 19.5 (molybdenum), 2.9 to 12.9 (copper) and 2.0 to 7.7 (REEs). Molybdenum therefore increases approximately 19-fold between the second and third 5-year period.

By the 2036-40 period, all minerals experience a 20-fold indexed demand increase, except for molybdenum and REEs. Furthermore, lithium and graphite both experience 41- and 54-fold demand increases compared with the 2020 baseline. This underpins the consequentially greater demand-induced pressure under a 'Delayed Transition' scenario compared with a 'Net Zero by 2050' scenario. Again, the average annual capacity additions modelled under the 'Delayed Transition' scenario cause significant demand-induced pressures across all focus minerals after 2030.

Figure 5. *Material-specific relative demand growth for each five-year step average (2025, 2030, 2035, 2040) for both scenarios ('Net Zero by 2050' and 'Delayed Transition' scenarios), indexed to 2020*

Appendix 4 – Limitations and Assumptions

There are three primary limitations to our methodology. First, the NGFS scenarios were not designed with the specific risk of raw materials in mind. Hence, there are limitations in the depth and coverage of the scenarios, which require addition assumptions to produce our analysis. Second, significant uncertainty exists in the estimation of future material demand, as well as for the data relating to mineral intensity for each technology. Third, there are limitations on estimating future supply, in both primary but especially secondary supply.

NGFS Model Limitations

The NGFS Climate Scenarios do not explicitly take material availability and related risks into account. The different sub-scenario models do not include all the necessary outputs to adequately estimate material demand from all low-carbon technology types, and their sub-technologies, limiting the extent to which total material demand can be assessed under different scenarios (Table 4). In light of these limitations, we use MESSAGE to estimate electricity generation and storage and GCAMS to estimate material demand from freight vehicles. None of the models are suitable to derive the required number of EVs under different scenarios, and we supplement using data from the EV Data Centre (EV Volumes, 2022) to projects estimated future material demand from EVs. The table below summaries the limitations of the NGFS model limitations for each technology type (the model used for each technology is highlighted in green).

Table: Summary of NGFS model limitations for analysing material demand

NGFS Model	Electricity Generation	Electricity Storage	Electricity Networks	Freight Vehicles	Electric Vehicles (EVs)
GCAMS	Fully included	Not included	Can be derived (with additional assumptions)	Can be derived (with additional assumptions)	Cannot be derived
MESSAGE	Fully included	Included	Can be derived (with additional assumptions)	Cannot be derived	Cannot be derived
REMIND	Included, no distinction between on-and-offshore wind	Included	Can be derived (with additional assumptions)	Cannot be Derived	Cannot be derived

Furthermore, because the NGFS Scenario IAMs assume allocative efficiency over an extended time horizon, offering a high-level narrative to inform decision-making over the medium to long term, outputs are provided in 5-year step averages. We therefore use a linear interpolation of technology capacity additions to provide annual deployment estimates. The interpolation is only used when deployment averages between 5-year periods is deemed significant, otherwise, the 5-year averages are used for each year in the period. This linear interpolation may slightly distort the scenarios, compared to their initial modelling. In this regard, the linear interpolation assumes a gradual and constant increase in technological deployment within 5-year periods. The purpose of the interpolation is to offer the smoothest increase in technological deployment, to not inadvertently exaggerate the rate of demand increases for different materials and consequently the potential demand-induced pressures.

Assumptions and Limitations for Future Material Demand

To estimate the material demand for the technology types considered (energy generation, electrical storage, EVs, freight vehicles and electrical networks), several assumptions were necessary to estimate future demand. The table below highlights the main assumptions which are used in the paper to extrapolate future material demand from the NGFS scenario outputs. These assumptions highlight the limitations to our analysis and the uncertainty in estimating future demand, and some of the dynamics that the paper is unable to capture.

Technology	Assumption	Limitations	Impact
All	10% linear improvement in material intensity between 2021-2040.	Does not capture the potential dynamics between commodity price increases and innovation; assumes the same rate of improvement for all technologies; uncertainty over the actual improvement in material intensity and potential limits.	Uncertain
All	Linear interpolation between 5-year periods.	Does not account for sudden changes in technological deployment in response to climate mitigation drivers–policy, consumer/investor sentiment, and technological advancement; the impact of short-term macroeconomic conditions on deployment.	Increases demand in some years and decreases demand in others to produce a smoother increase in low-carbon technological deployment.
Energy Generation, Electrical Storage, EVs, Freight	IEA's base case scenario for sub-technology market share.	Does not capture the potential dynamics between commodity price increases and innovation; assumes linear change in market share. Also excludes new technologies which may emerge.	Overestimate demand in the long-term for some materials as substitutional dynamics are only partially accounted for.
Electrical Storage	Fixed battery discharge rate.	Battery size directly relates to discharge rate. Therefore, assuming a different discharge rate would significantly change the estimates for material demand. Moreover, we assume the same discharge rate for all electrical storage worldwide.	Uncertain
Electrical Storage	Exclusion of Hydrogen	Hydrogen fuel cells are identified as a potential alternative to battery storage, which are excluded from this study.	Overestimation of battery materials (particularly in the long-term).
EVs	EVs numbers are taken from the EV Data Centre.	These numbers are exogeneous to the NGFS scenario and do not account for the differing scenario narratives around the climate transition. The projections align closely with the NZ scenario, but not the DS scenario.	Uncertain (NZ), Increase in EV material demand in the short term (DS)

EVs	EV annual deployment is maintained post-2035 to 2040.	This assumes no growth in EV sale volumes post-2035.	(Possibly) underestimates EV demand post-2035.
Freight Vehicles	Number of vehicles calculated through total energy-use.	This introduces various assumptions on freight vehicles including standardized energy-use between vehicles, average distance travelled and lifespan of vehicles.	Uncertain
Freight Vehicles	Exclusion of Hydrogen	Hydrogen fuel cells have been identified as a potential alternative for HGVs.	May lead to an overestimation in battery metals (particularly in the long term).
Network Grids	NGFS regional groupings are not as detailed as data on network grids.	The NGFS regional breakdown is more aggregated than the data on network grids, so regional averages had to be used. This leads to less precise estimation of material requirements for each region.	Mixed
Network Grids	Ratio of overhead versus underground lines and substitutional use of aluminum	The ratio of overhead to underground lines is taken from the European average and applied globally (due to a lack of data). Aluminium is a substitute for copper in electrical network grids, particularly in overhead cables. Hence, the fixed ratio applied assumes a constant ratio between copper and aluminium use over time.	Uncertain/overestimation of copper demand.

Assumptions and Limitations for Projected Future Primary and Secondary Supply for Copper, Nickel, and Lithium.

Primary Supply

Projected primary supply, up to 2030, is taken from S&P Global Capital IQ Pro (S&P Global, 2022b). This includes all (or at least the vast majority) of industrial mining globally, at a mine-by-mine level analysis for all current as well as announced future mines. However, artisan and small-scale mining (ASM) is not included due to the lack of reporting on these mines. Beyond 2030, the projections indicate supply falling, which is assumed to be due to the retirement of currently operational mines and the lack of future mining projects that are announced at this point. We decide this is an unlikely outcome and not consistent with historical supply, which shows primary supply to be on a continuous upwards trend. Consequently, the growth rate in supply between 2021-2030, as projected by S&P Global, is assumed for the following time-period of 2031-2040. This assumption is used to overcome the data limitations with S&P Global's projections post-2030; however, it does not capture the supply price elasticity, or the response of mining companies in response to an increase in demand (signalled through higher prices for commodities). Hence, the assumption is likely to underestimate primary supply considering the expected climate transition, particularly in the long-term where primary supply is less price inelastic due to long development lead times for new mines.

Further assumptions are necessary to examine the future primary supply of nickel. The projections by S&P Global indicate primary supply to be substantially below the historical numbers found in U.S. Geological Surveys (USGS, 2022b). This is because there is substantial nickel production in Indonesia by private companies and is not captured in the S&P analysis. Hence, if the S&P Global projections were used, it would substantially overestimate the potential of material bottlenecks. Consequently, the historical growth rate of primary nickel supply, from 2011-2020 is applied to 2021 production, using data from the U.S. Geological Surveys. The same growth rate is also applied for projected primary supply between 2031-2040. Again, this assumption is necessary to overcome the data limitations; however, it fails to capture the relationship between expected future demand and supply increases.

Secondary Supply

As discussed in the methodology, the secondary supply is calculated using the lifespan of end-use sectors and the recycling rate of each material. Whilst the technological lifespan is known for the clean technology sectors, we did not have data for the lifespan for all other sectors where these materials are used. This is particularly problematic for copper and nickel, which are used extensively in other applications outside of clean technologies. To overcome this limitation, we assume the same technology lifespan for all sectors to calculate the expected secondary supply. This assumption likely overestimates secondary supply, particularly in the short-term, because some uses for copper and nickel are likely to be significantly longer in other end-use sectors, such as construction. Our hypothesis of the overestimation of secondary supply is supported by IEA (2021a) analysis, which shows secondary supply to be significantly lower, especially in the short-term.

For the recycling rate, we assume a fixed recycling rate based on currently available data on material recycling rates. However, the recycling rates of materials is likely to increase in the future due to stricter environmental regulation as well as potentially higher commodity prices. We do not take this into account because it is not possible to accurately estimate the increase in recycling rates. Consequently, the analysis likely underestimates secondary supply in the long run by failing to capture the dynamics between future policy and prices, and recycling rates. However, this underestimation is likely to be partially offset by the overestimation that stems from the shorter technology lifespan for materials in other sectors.