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Impacts of climate change on mining, related environmental risks and raw material supply

Final report

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Impacts of climate change on mining, related environmental risks and raw material supply

Final report

by

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Abstract: Impacts of climate change on mining, related environmental risks and raw material supply

The project "Impacts of climate change on the environmental criticality of Germany's raw material demand" (KlimRess), commissioned by the German Environment Agency (*Umweltbundesamt*, UBA), is one of the first research projects on the potential impacts of climate change on mining. The project team comprised adelphi, ifeu Heidelberg and the Sustainable Minerals Institute of the University of Queensland. The aim of the project was to assess how climate change potentially affects the environmental risks of mining and raw material supply chains. This final report summarises the research results of the project.

The report offers insights on climate change impacts from five qualitative case studies, providing answers to the questions: *How are environmental risks of mining impacted by climate change? How are raw material supply chains affected?* Furthermore, the report presents and discusses the results of a quantitative climate change vulnerability assessment of main producing countries and reserves of bauxite, coking coal, copper, iron ore, lithium, nickel, PGMs, tin, and tungsten, focussing on the following questions: *Which raw material-producing countries are comparatively more at risk from climate change? What conclusions can be drawn about the global primary production of certain raw materials and their vulnerability to climate change? How might these risks change in the future?*

Kurzbeschreibung: Auswirkungen des Klimawandels auf den Bergbau, damit verbundene Umweltrisiken und die Versorgung mit Rohstoffen

Das im Auftrag des Umweltbundesamtes (UBA) durchgeführte Projekt „Auswirkungen des Klimawandels auf die ökologische Kritikalität des deutschen Rohstoffbedarfs" (KlimRess) ist eines der ersten Forschungsprojekte zu den möglichen Auswirkungen des Klimawandels auf den Bergbau. Das Projektteam bestand aus adelphi, dem ifeu (Institut für Energie- und Umweltforschung Heidelberg) und dem Sustainable Minerals Institute der University of Queensland. Ziel des Projekts war es, zu untersuchen, wie sich der Klimawandel potenziell auf Umweltrisiken des Bergbaus sowie auf Rohstofflieferketten auswirkt. Der vorliegende Abschlussbericht fasst die Forschungsergebnisse des Projekts zusammen.

Der Abschlussbericht stellt Erkenntnisse aus fünf qualitativen Fallstudien, die die Auswirkungen des Klimawandels in fünf Ländern und für neun Rohstoffe untersuchen, dar und beantwortet die folgenden Forschungsfragen: *Wie werden die Umweltrisiken des Bergbaus durch den Klimawandel beeinflusst? Wie sind die Rohstofflieferketten betroffen?* Darüber hinaus präsentiert der Bericht die Ergebnisse einer quantitativen Klimawandelvulnerabilitätsanalyse für Produktionsländer und Reserven von Bauxit, Eisenerz, Kokskohle, Kupfer, Lithium, Platinmetallen, Wolfram und Zinn und beantwortet folgende Fragen: *Welche rohstoffproduzierenden Länder sind vergleichsweise stärker vom Klimawandel betroffen als andere? Welche Rückschlüsse lassen sich auf die globale Primärproduktion bestimmter Rohstoffe und ihre Klimawandelvulnerabilität ziehen? Wie könnten sich diese Risiken in Zukunft verändern?*

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AMD	Acid mine drainage
ASM	Artisanal and small-scale mining
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe (German Federal Institute for Geosciences and Natural Resources)
DRC	Democratic Republic of the Congo
EHP	Environmental hazard potentials
GHG	Greenhouse gas
ICMM	International Council on Mining & Metals
IPCC	Intergovernmental Panel on Climate Change
KlimRess	Research project: Impacts of climate change on the environmental criticality of Germany's raw material demand
LSM	Large-scale mining
ND-GAIN	Notre Dame Global Adaptation Country Index
OekoRess	Research project: Discussion of the environmental limits of primary raw material extraction and development of a method for assessing the environmental availability of raw materials to further develop the criticality concept (OekoRess I)
PGMs	Platinum group metals
REE	Rare Earth Elements
USA	United States of America
WSI	Water Stress Index

Summary

Part 1: Insights on climate change impacts from five case studies

The first part of this report presents the results of the five qualitative case studies that assessed the impacts of climate change in five countries and for nine raw materials and answers the following research questions: *How are environmental risks of mining impacted by climate change? How are raw material supply chains affected?*

Too much water versus too little water: Extreme weather events as main risks

Extreme weather events, in particular flooding, stand out as the main risk, both in terms of environmental impacts and of disruption of supply across different raw materials, mining sites and climatic zones. Whether caused by heavy rain, tropical cyclones, snow melt or storm surges, flooding poses a serious risk because it can lead to wash outs or spills of hazardous or toxic substances from mining pits or waste storage. Failures of large tailings dams are particularly dangerous as they not only result in extensive environmental damage but often also destroy livelihoods, damage infrastructure and even cause fatalities.

However, having too little water also poses risks to mining. Drought can lead to water shortages, affecting both environmental aspects (e.g. less water available for dust suppression) and supply aspects (e.g. water-intensive production processes need to be slowed down). In addition, increased water stress might intensify water competition between mining and other water users (e.g. communities or agriculture).

Biodiversity, rehabilitation and communities are impacted by multiple climate impacts

Another main finding is that a broad range of climate impacts affects biodiversity and rehabilitation. All of the assessed climate impacts potentially impede revegetation and rehabilitation efforts at mining sites. The long timeframe of rehabilitation efforts also plays an important role as climate change impacts are projected to be more pronounced in the future.

Climate change has a negative impact not only on biodiversity and rehabilitation, but also on people living in mining regions. Communities are under pressure from multiple stressors (e.g. social inequality, water stress and mining). Climate change acts as a 'risk multiplier', putting additional pressure on communities.

Indirect climate change impacts on land and energy use

Open pit mining, with large overburden and tailings, has a significant land footprint. In most cases, climactic changes will not directly cause an increase in the size of the mining pit or tailings. However, there may be indirect impacts: climate change might lead to an increase in land use if mining companies abandon existing mining sites and move operations for example because of flooding , or open new mining projects at other locations to diversify their operations. In addition, land use might indirectly increase due to new infrastructure requirements caused by climate change (e.g. desalination plants or solar panels).

We do not expect climate change to directly increase energy use at mines, but there might be indirect impacts: for example increased water scarcity may require sea water desalination or increased on-site water pumping, leading to a higher energy demand.

Only a few, ambiguous positive impacts

There are only two potential positive climate change-related impacts across the case studies. In addition, the case studies showed that positive impacts are very site-specific and depend on the local situation. Overall, the potential negative impacts clearly outweigh the positive ones.

The research results cannot replace individual vulnerability assessments at mining or production sites

The climate change impacts identified in the case studies and summarised in this report represent a range of potential effects on mining and processing sites. However, this analysis cannot give a complete picture because other assessments, whether on the ground, at other sites or in different contexts, may identify additional or different climate change impacts. Individual vulnerability assessments are therefore necessary to assess risks specific to a mining or production site.

Part 2: Climate change vulnerability assessment of main producing countries and reserves

The second part of the report presents the results of the quantitative vulnerability assessment of key producing countries (production and reserves) and answers the following questions: *Which raw material-producing countries are comparatively more at risk from climate change? What conclusions can be drawn about the global primary production of certain raw materials and their vulnerability to climate change? How might these risks change in the future?*

Tin, bauxite, copper and nickel production takes place in the most vulnerable countries

The climate change vulnerability assessment of nine raw materials showed that tin, bauxite, copper and nickel are among the most vulnerable raw materials as large shares of their production and reserves are located in countries highly vulnerable to climate change. The share of bauxite and copper reserves in vulnerable countries is larger than the share of bauxite and copper production. This indicates that the vulnerability of bauxite and copper production might increase in the future.

Iron ore, tungsten and coking coal-producing countries are less vulnerable

The production and reserves of iron ore, tungsten and coking coal lie in comparatively less vulnerable countries. Countries with a higher vulnerability have a larger share of coking coal reserves than of coking coal production, suggesting that the vulnerability of coking coal production could potentially increase in the long term.

PGMs and lithium production is located in the least vulnerable countries

The production and reserves of PGMs and lithium are located in the comparatively least vulnerable countries. Notably, though, both production and reserves are highly concentrated (PGMs production and reserves in two countries, lithium production and reserves in four countries). If production in one country failed due to climate change impacts, there would be few alternative suppliers.

Exposition and adaptive capacity are important components when understanding vulnerability

Past extreme weather events show that even if the adaptive capacity of a country is high, it does not mean that climate change cannot have any negative effects. No country with raw material production or reserves covered in this report has low exposure. This indicates that that all production sites, regardless of their adaptive capacity, can potentially be affected by climate change impacts and that preparing for negative climate change impacts is crucial for all countries.

Limitations of the vulnerability assessment and further considerations

With regard to the results of the vulnerability assessment, it should be kept in mind that vulnerability indexes cannot capture all dimensions of climate change vulnerability. However, an indicator-based assessment can serve as a starting point to identify potentially vulnerable countries whose raw material production can be examined closer in a next step.

Future research projects could focus on additional aspects. Instead of assessing the vulnerability of production and reserves, future projects could base the assessment on data for individual mining sites or mineral deposits, though data on vulnerability at this scale is limited. The exposure of mining sites or mineral deposits, however, could be assessed based on spatial data of downscaled climate change projections.

Zusammenfassung

Teil 1: Erkenntnisse aus fünf qualitativen Fallstudien über Auswirkungen des Klimawandels auf den Bergbau

Der erste Teil des Berichts stellt Erkenntnisse aus fünf qualitativen Fallstudien, die Auswirkungen des Klimawandels in fünf Ländern und für neun Rohstoffe untersuchen, dar und beantwortet die folgenden Forschungsfragen: *Wie werden die Umweltrisiken des Bergbaus durch den Klimawandel beeinflusst? Wie sind Rohstofflieferketten betroffen?*

Zu viel Wasser versus zu wenig Wasser: Extremwetterereignisse als Hauptrisiko

Extremwetterereignisse, insbesondere Überschwemmungen, stellen das Hauptrisiko dar, sowohl in Bezug auf die Umweltauswirkungen als auch auf die Unterbrechung der Versorgung. Dies gilt für alle untersuchten Rohstoffe, Bergbaugebiete und Klimazonen. Ob durch Starkregenereignisse, tropische Wirbelstürme, Schneeschmelze oder Sturmfluten verursacht, Überschwemmungen stellen ein ernstzunehmendes Risiko dar, da sie zu Auswaschungen oder zum Austreten von gefährlichen oder giftigen Stoffen aus Bergwerksgruben oder Bergbaureststoffen führen können. Besonders gefährlich ist es, wenn die Rückhaltefunktion von großen Absatzbecken versagt, da solch ein Ereignis nicht nur zu erheblichen Umweltschäden führen, sondern auch Lebensgrundlagen zerstören, Infrastrukturen beschädigen und im schlimmsten Fall sogar Todesopfer fordern kann.

Zu wenig Wasser birgt jedoch auch Risiken für den Bergbau. Dürre kann zu Wasserknappheit führen, die sowohl Umweltaspekte (beispielsweise weniger Wasser zur Staubbekämpfung) als auch Versorgungsaspekte (beispielsweise müssen die wasserintensive Prozesse gedrosselt oder unterbrochen werden) betrifft. Darüber hinaus könnte eine erhöhte Wasserknappheit Nutzungskonflikte um Wasser zwischen dem Bergbau und der Weiterverarbeitung auf der einen Seite und anderen Wassernutzern (z.B. die lokale Bevölkerung oder Landwirtschaft) auf der anderen Seite verschärfen.

Biodiversität, Rekultivierung und die lokale Bevölkerung sind von vielfältigen Klimaauswirkungen betroffen

Ein weiteres wichtiges Ergebnis ist, dass ein breites Spektrum von Klimaauswirkungen die Biodiversität und die Rekultivierung und Sanierung von ehemaligen Bergwerken beeinflussen. Alle von den Fallstudien betrachteten Klimaauswirkungen beinträchtigen potenziell die Rekultivierung und Sanierung von Bergbaustandorten. Auch der lange Zeithorizont der Rekultivierungs- und Sanierungsmaßnahmen spielt eine wichtige Rolle, da die Auswirkungen des Klimawandels in Zukunft zunehmen.

Der Klimawandel hat nicht nur negative Auswirkungen auf die Rekultivierungs- und Sanierungsmaßnahmen, sondern auch auf die Menschen, die in Bergbauregionen leben. Die lokale Bevölkerung ist dabei mit einer ganzen Reihe von Problematiken konfrontiert (beispielsweise soziale Ungleichheit, Wasserknappheit und Bergbau). Der Klimawandel fungiert als „Risikomultiplikator“ und übt zusätzlichen Druck auf die Bevölkerung aus.

Indirekte Auswirkungen des Klimawandels auf Land- und Energieverbrauch

Tagebaue mit großen Abraum- und Haldenflächen haben einen erheblichen Flächenbedarf. In den meisten Fällen werden klimatische Veränderungen nicht zu einer Vergrößerung von Gruben oder zu einer Vergrößerung von Reststoffmengen führen. Es können jedoch indirekte

Auswirkungen auftreten: Der Klimawandel kann zu einer Zunahme der Landnutzung führen, wenn Bergbauunternehmen wegen des Klimawandels Gruben aufgeben, den Abbau an anderen Gruben, die nicht oder weniger betroffen sind, steigern oder neue Bergbauprojekte an anderen Standorten eröffnen, um ihren Betrieb zu diversifizieren. Darüber hinaus könnte die Landnutzung indirekt durch neue Infrastrukturanforderungen (z.B. Entsalzungsanlagen oder Solarmodule) zunehmen.

Es wird nicht erwartet, dass der Klimawandel den Energieverbrauch des Bergbaus direkt erhöht, aber es können indirekte Auswirkungen auftreten, zum Beispiel: Eine zunehmende Wasserknappheit kann Meerwasserentsalzung oder eine gesteigerte Wasserförderung vor Ort erfordern, was zu einem höheren Energiebedarf führen kann.

Nur wenige und nicht eindeutige positive Klimawandelauswirkungen konnten festgestellt werden

In den Fallstudien traten nur zwei potentielle, positive, klimabedingte Auswirkungen auf. Die Fallstudien zeigen, dass die identifizierten potenziellen positiven Auswirkungen sehr genau betrachtet werden müssen. Die positiven Folgen sind sehr spezifisch und hängen stark vom lokalen Kontext ab. Insgesamt überwiegen die möglichen negativen Auswirkungen deutlich gegenüber den positiven.

Die vorliegenden Forschungsergebnisse können spezifische Klimawandelvulnerabilitätsanalysen an Bergbau- oder Produktionsstandorten nicht ersetzen

Die in den Fallstudien identifizierten und in diesem Bericht zusammengefassten Auswirkungen des Klimawandels stellen eine Reihe möglicher Auswirkungen auf Bergbaustandorte und Standorte der Weiterverarbeitung dar. Der Bericht kann jedoch keine allumfassende Analyse liefern, da zusätzliche oder anders ausgeprägte Klimawandelauswirkungen an verschiedenen Standorten identifiziert werden können, zum Beispiel wenn Untersuchungen vor Ort, bezüglich anderer Standorte oder in unterschiedlichen Kontexten durchgeführt werden. Spezifische Klimawandelvulnerabilitätsanalysen sind daher notwendig, um Risiken zu bewerten, die an einem bestimmten Bergbau- oder Produktionsstandort auftreten können.

Teil 2: Quantitative Klimawandelvulnerabilitätsanalyse von Bergbauländern

Im zweiten Teil des Berichts werden die Ergebnisse einer quantitativen Klimawandelvulnerabilitätsanalyse für wichtige Bergbauländer (Abbau und Reserven) vorgestellt, wobei die folgenden Fragen beantwortet werden: *Welche rohstoffproduzierenden Länder sind vergleichsweise stärker vom Klimawandel betroffen als andere? Welche Rückschlüsse lassen sich auf die globale Primärproduktion bestimmter Rohstoffe und ihre Klimawandelvulnerabilität ziehen? Wie könnten sich diese Risiken in Zukunft verändern?*

Zinn-, Bauxit-, Kupfer- und Nickelförderung finden in den am stärksten vom Klimawandel gefährdeten Ländern statt

Die Klimawandelvulnerabilitätsanalyse von neun Rohstoffen ergab, dass Zinn, Bauxit, Kupfer und Nickel zu den am stärksten gefährdeten Rohstoffen gehören, da große Teile ihrer Produktion und Reserven in Ländern liegen, die stark vom Klimawandel betroffen sind. Der Anteil der Bauxit- und Kupferreserven in gefährdeten Ländern ist größer als der Anteil der Bauxit- und Kupferproduktion. Dies deutet darauf hin, dass die Anfälligkeit der Bauxit- und Kupferproduktion in Zukunft zunehmen könnte.

Länder, die Eisenerz, Wolfram und Kokskohle fördern, sind im Vergleich weniger gefährdet

Die Förderung und Reserven von Eisenerz, Wolfram und Kokskohle befinden sich in vergleichsweise weniger gefährdeten Ländern. Länder mit einer höheren Vulnerabilität haben einen größeren Anteil an den Kokskohlereserven als an der Kokskohleförderung, was darauf hindeutet, dass die Anfälligkeit der Förderung von Kokskohle langfristig möglicherweise zunehmen könnte.

Die Förderung von Platinmetallen und Lithium befindet sich in den am wenigsten vom Klimawandel gefährdeten Ländern

Die Förderung und die Reserven von Platinmetalle und Lithium findet im Vergleich in den am wenigsten gefährdeten Ländern statt. Herauszustellen ist jedoch, dass sowohl die Förderung als auch die Reserven in wenigen Ländern konzentriert sind (Platinmetalle in zwei Ländern, Lithium in vier Ländern). Wenn die Förderung in einem Land auf Grund von Klimawandelauswirkungen reduziert würde, gäbe es daher nur wenige alternative Lieferanten für den jeweiligen Rohstoff.

Die Exposition und die Anpassungsfähigkeit eines Landes sind wichtige Komponenten bei der Betrachtung von Vulnerabilität

Ereignisse in der Vergangenheit zeigen, dass selbst wenn die Anpassungsfähigkeit eines Landes an den Klimawandel stark ausgeprägt ist, es nicht ausgeschlossen ist, dass der Klimawandel negative Auswirkungen haben kann. Keines der untersuchten Länder mit Rohstoffförderung oder -reserven ist Wetter- und Klimawandel nur in geringem Maße ausgesetzt, d.h. das Ausmaß der Exposition gegenüber den Gefahren des Klimawandels ist in allen Ländern mittel bis sehr hoch. Dies zeigt, dass alle Produktionsstandorte, unabhängig von ihrer Anpassungsfähigkeit, potenziell von den Auswirkungen des Klimawandels betroffen sein können und dass die Vorbereitung auf negative Auswirkungen des Klimawandels für alle Länder entscheidend ist.

Einschränkungen bei der quantitativen Vulnerabilitätsanalyse und weiterführende Überlegungen

Im Hinblick auf die Ergebnisse der Vulnerabilitätsanalyse sollte bedacht werden, dass quantitative Indikatoren, die die Vulnerabilität eines Landes anzeigen, nicht alle Dimensionen der Vulnerabilität gegenüber dem Klimawandel erfassen können. Die Bewertung mit Indikatoren kann jedoch als Ausgangspunkt dienen, um potenziell stärker gefährdete Länder zu identifizieren und deren Rohstoffproduktion dann in einem weiteren Schritt genauer zu untersuchen.

Zukünftige Forschungsprojekte könnten weitere Aspekte einbeziehen. Anstatt die Vulnerabilität von Bergbauländern zu betrachten, könnten zukünftige Projekte die Bewertung auf Daten für einzelne Abbaustätten oder Lagerstätten stützen, obwohl Daten über Klimawandelvulnerabilität mit einer derartigen Granularität nur begrenzt verfügbar sind. Die Exposition von Bergbaugebieten oder Lagerstätten könnte jedoch auf der Grundlage von räumlichen Daten aus herunterskalierten Klimaschutzprognosen bewertet werden.

1 Background of the report

The project "Impacts of climate change on the environmental criticality of Germany's raw material demand" (KlimRess), commissioned by the German Environment Agency, is one of the first research projects on the potential impacts of climate change on mining. The project team, consisting of adelphi, ifeu Heidelberg and the Sustainable Minerals Institute of the University of Queensland, Australia, assessed how climate change can potentially impact the environmental risks of mining and tried to answer the question of how climate change might affect raw material supply chains. This final report summarises the research results of the project.

At the outset, five case studies, covering different climatic areas and governance contexts, provided an exploratory analysis of how climate change impacts can aggravate existing environmental risks in mining and potentially disrupt supply chains (see Chapter 2). The case studies have also been published as individual reports (Rüttinger et al. 2020a-e). By carrying out a systematic assessment of the case study results, the project team identified the most significant climate impacts across case studies (see Chapter 2.2). The project team also explored linkages between climate change and a novel method to evaluate environmental hazard potentials as part of an environmental criticality assessment (OekoRess method) in order to contribute to the discussion of environmental criticality (see Chapter 2.3). In addition, the project team combined data on current production and expected future production of nine raw materials with data on countries' vulnerability to climate change in order to identify patterns of particularly vulnerable raw materials and producing countries (see Chapter 3). The project team draws conclusions in the final chapter of the report (see Chapter 4).

As a result of these steps, the project team developed recommendations on how to best adapt the mining sector, incentivise climate change adaptation measures in the mining sector and how to foster effective mechanisms for sharing knowledge and expertise on this topic globally. The project team published these policy recommendations separately in the form of a recommendation paper (van Ackern et al. 2020).

To validate and disseminate the project's preliminary results, the project team organised an expert workshop in November 2018. Furthermore, the insights gained during the project were presented to the broader public at the Raw Materials and Environment Conference under the auspices of the German Environment Agency in February 2019 and further discussed with participants during an additional workshop at the conference. In this context, the team drafted and disseminated a conference and a discussion paper containing the most important aspects of the project for the conference audience and policymakers.

2 Insights on climate change impacts from five case studies

The case studies conducted as part of the project covered five different (climatic) regions:

1. Arid regions with water stress
2. Humid tropical regions
3. Polar or subpolar regions
4. Temperate regions
5. Coastal regions

In addition, the case studies cover nine raw materials that were identified and selected based on the following criteria:

- The importance of minerals and metals for future and environmental technologies: A list of potential priority raw materials was identified based on the analysis of studies on future and environmental technologies (Buchert et al., 2019; Marscheider-Weidemann et al., 2016; Schriefl and Bruckner, 2016). The raw materials with a future "scarcity-factor" above one[1] were lithium, platinum group metals (PGMs), rare earth elements (REE) and tin.
- Base metals, alloys and auxiliary materials important for the German economy: Base metals, alloys and auxiliary materials important for the German economy were identified based on the report on the national raw material situation of the Federal Institute for Geosciences and Natural Resources (*Bundesanstalt für Geowissenschaften und Rohstoffe*, BGR) (Huy et al., 2016). Aluminum, tin, copper, iron, PGMs, silver and coking coal are highly significant for Germany's economy, and Germany is highly dependent on imports of these materials.

The selected metals and minerals are bauxite, coking coal, copper, iron ore, lithium, nickel, PGMs, tin and tungsten.

Other criteria that informed the case study selection were the climate change vulnerability of countries, their governance contexts and the prevalence of conflicts related to mining. The aim was to select a set of most different cases. Further selection criteria were the political relevance for Germany, the research institutions' partner networks and the availability of data.

The selected five countries and nine minerals and metals are shown in Table 1. Each case study analysed the chosen mine site and the processing steps (to the extent these take place in the relevant country). For each of the mining and processing sites, we evaluated environmental and supply risks potentially caused by climate stimuli and/or direct climate impacts.

The case studies are based on extensive secondary research, including the scientific literature, as well as reports and statements published by national government agencies, civil society organisations, mining and processing companies and the media.

[1] Future demand will exceed current world production by more than 100%.

Table 1: Overview five country case studies

Country	Raw material	Locations	Climate/region
Australia	Bauxite	Weipa mining site	Tropical, winter dry/coastal
		Gladstone refinery and smelter	Humid subtropical/coastal
	Iron ore	Mount Whaleback mining area	Hot desert
	Coking coal	Goonyella Riverside mine	Hot semi-arid
Chile	Copper	Antofagasta, Escondida mine	Cold semi-arid
		Coloso, concentrate filter plant	Cold desert climate
	Lithium	Antofagasta, Salar de Atacama mine	Cold semi-arid
Canada	Nickel	Voisey's Bay mine	Subarctic/polar tundra
		Long Harbour refinery	Humid continental/subartic
	Tungsten	Cantung mine	Subarctic/polar tundra
Indonesia	Tin	Bangka, Belitung on- and offshore mining	Tropical rainforest
		Mentok smelter	Tropical rainforest
South Africa	PGMs and nickel	Mogalakwena mine	Arid to temperate
		Polokwane, smelter	Mild temperate climate/subtropical climate
		Rustenburg, refineries	Arid to temperate

2.1 Systematic assessment of the case studies

2.1.1 Environmental categories, climate stimuli and direct climate impacts

To begin, the project team developed a set of mining-related environmental categories for the climate change impact assessment. The selected environmental categories are:

- Land use
- Water use
- Energy use
- Waste
- Air emissions

- Rehabilitation
- Biodiversity
- Health

A comprehensive description of each of the environmental categories and potential climate change induced impacts for each category is provided in Appendix A, Table 24.

In addition to the environmental categories, we categorised climate stimuli and direct climate for the assessment. Table 2 shows the categories of climate stimuli and direct climate impacts used, sorted into two groups, 'slow-onset, gradual change' and 'sudden-onset, extreme events'. Both groups of climate change phenomena are of a complex nature. Short-term impacts are easier to grasp than long-term, slowly occurring impacts, and therefore there is more information available on the former. In addition, it has to be taken into account that weather extremes also occur independently from climate change. However, climate change projections expect these to occur more frequently and/or be more intense in the future, depending on the weather phenomenon and the region. A comprehensive description of the climate stimuli and direct climate impacts as well as potential impacts on the environment and supply is presented in Appendix A, Table 25.

Table 2: Overview of climate stimuli and direct climate impacts

<table>
<tr><th colspan="2">Climate stimuli and direct climate impacts</th></tr>
<tr><td>Slow-onset, gradual change</td><td>Sudden-onset, extreme events</td></tr>
<tr><td>Increase of mean temperature</td><td>Occurrence of heat waves</td></tr>
<tr><td>Increase of mean precipitation</td><td>Occurrence of wildfires</td></tr>
<tr><td>Decrease of mean precipitation</td><td>Occurrence of heavy rain events</td></tr>
<tr><td colspan="2">Occurrence of droughts[2]</td></tr>
<tr><td></td><td>Occurrence of flooding events</td></tr>
<tr><td colspan="2">Occurrence of erosion/landslide</td></tr>
<tr><td>Sea warming</td><td>Occurrence of cyclones/typhoons/hurricanes</td></tr>
<tr><td>Permafrost degradation</td><td>Occurrence of heavy waves/storm surge</td></tr>
<tr><td>Melting glaciers</td><td>Occurrence of heavy wind</td></tr>
</table>

Source: Categorisation developed in the project

In each of the case studies, we analysed the interrelations between climate stimuli and direct climate impacts on the mining site and processing sites situated within the country. In addition, we carried out a separate analysis on climate stimuli and direct climate impacts that could potentially disrupt the supply chain (from mining site to export destination).

In general, the supply chain analysis covered the following sites and steps of the supply chain, if applicable:

- Mining site

[2] Droughts are an extreme weather event, but are linked to slow-onset change (UNFCCC, 2012).

- Processing plants (refinery, concentrator plant, smelter)
- Transports (via routes, via sea, air transports, railway, pipeline)
- Port
- Work force

2.1.2 Site-specific assessment grids

In order to provide comparable results across cases, we used two kinds of assessment matrixes to qualitatively assess the potential climate change impacts identified in the climate change impact assessments. They are:

1. Assessment matrixes summarising, for each mining site and processing site, the potential effects of climate stimuli and of direct climate impacts on (potential and already existing) environmental impacts
2. Assessment matrixes summarising the potential for supply interruptions showing the potential climate impacts on infrastructure and transportation routes

The identified potential climate impacts were – for each raw material (for potential effects on both current environmental impacts/risks and the supply chain) – classified using the following main categories:

- **Negative potential climate impact**: Projected climatic changes are expected to affect environmental impacts or security of supply negatively.
- **Positive potential climate impact**: Projected climatic changes are expected to affect environmental impacts or security of supply positively.
- **No potential climate impact**: Projected climatic changes are not expected to affect environmental impacts or security of supply.
- **Difficult to evaluate**: The potential impacts of projected climatic changes are difficult to evaluate (e.g. because of lacking data or high uncertainty).

The data available for the case studies did not allow any further sub-classification of negative potential climate impacts (e.g. high or medium negative potential climate impacts). It was only possible to assess whether a negative potential climate impact is expected to occur or not, not the severity of such an impact. Figure 1 shows parts of the assessment matrix for the Mogalakwena mine in South Africa as an example. The four different categories are colour coded, i.e. red for identified negative potential climate impacts and blue in case no potential climate impact could be detected.

Figure 1: Details of the assessment grid for the Mogalakwena mine in South Africa

CC and environmental impacts: PGMs and nickel mining

Climate Stimuli and Direct Climate Impacts / Environmental impacts	Land use	Water use	Energy use	Waste	Ai
	The major land use and disturbance includes open pits, tailings storage facilities, waste-rock dumps, as well as roads and infrastructure. The company aims to perform progressive land rehabilitation, where possible, to agreed (with communities and government regulators) land-use specifications (Anglo American Platinum, 2018b). The area surrounding the mine is mainly used for commercial grazing and agricultural purposes; a few rural settlements are also adjacent to the mine.	The mine is located in a water deficient area, where there is a growing (and competing) demand for water from agricultural, mining, industrial and domestic use. The expansion of Mogalakwena mine would potentially be hindered by limited water access, as well as on-going drought conditions. The use of alternative water sources such as pit water at the mine site, waste water from other organisations and municipalities (delivered via a pipeline), and connecting to other water dams in the area are all parts of the company's water strategy (Anglo American, 2018a). In 2016, about 66% of water requirements at all Anglo American Platinum operations were met by recycling and reuse, while new water is primarily withdrawn from ground sources (Anglo American Platinum, 2018b).	In general, mining and beneficiation processes account for about 70% of total energy requirements to produce PGMs (IPA, 2015). The major energy use at Mogalakwena mine is associated with the ore beneficiation processes (crushing, grinding and flotation), ore transportation (by haul trucks), and the use of explosives in the open pit. The major electricity supply is from the South African national grid, mainly based on coal fired power generation. The company has long term commitments to reducing energy consumption and investigates opportunities for carbon offsetting (Anglo American Platinum, 2018b). A solar photovoltaic project at Mogalakwena complex is currently under consideration (Anglo American, 2018d). No details on energy consumption at the mine site has been disclosed to date.	The major waste from PGM mining is in the form of waste rock and tailings. At Mogalakwena, some waste rock dumps are classified as low grade PGM ore, and can be re-mined under favourable economic conditions; waste rock is also used for processing into aggregates for construction and road building (Anglo American Platinum, 2018b). Due to the presence of sulphides in the ore body (such as pyrrhotite, pyrite, chalcopyrite and pentlandite), there is a potential for acid mine drainage from mine waste (Zientek et al., 2017). Appropriate waste management techniques are required for tailings deposition and storage during the operational stage, and for land rehabilitation at the end of mine life, including revegetation, dust management and water management.	Nc (in mi to em exp
Increase of mean temperature	No significant potential climate impact expected	No significant potential climate impact expected	No significant potential climate impact expected	No significant potential climate impact expected	Nc im
Decrease of mean temperature					
Increase of mean precipitation					
Decrease of mean precipitation (some projections indicate insignificant changes to present-day precipitation)	No significant potential climate impact expected	No significant potential climate impact expected	No significant potential climate impact expected	No significant potential climate impact expected	Nc im
Heat waves	No significant potential climate impact expected	No significant potential climate impact expected	No significant potential climate impact expected	No significant potential climate impact expected	Nc im
Drought	No significant potential climate impact expected	Negative potential climate impact: Less water availability (needed for mining processes and dust control)	No significant potential climate impact expected: no energy supply from hydropower	Negative potential climate impact: The concentrations of metals, sulfate, and acidity in mining pits, leach pads and tailings could increase during prologend dryspells (see Nordstrom 2009)	Ne Le co
Fires	No significant potential climate impact expected	No significant potential climate impact expected	No significant potential climate impact expected	No significant potential climate impact expected	Nc im
Heavy rain	Heavy rain can lead to flooding				
	No significant potential climate impact	No significant potential climate impact expected	No significant potential climate	Negative potential climate impact:	Nc

PGMs and nickel mining site | Smelter | Base Metal Refinery | Precious Metal Refinery | Supply (all locations)

Source: Screenshot of assessment grid.

2.1.3 Qualitative modelling

Based on the results from the assessment matrixes, the links between climate change and the environmental impacts and risks of extracting raw materials were systematically compiled and presented in a qualitative model.

Modelling in iModeler[3] was used to bundle the core aspects and central links, first in a model for each case study, and second in a superordinate model. The modelling allowed a better understanding of the causal context of climate change aspects on environmental impacts and risks and supply risks. However, the modelling could only be done in a descriptive manner due to the challenges and limits of assessing the potential climate change impact in the case studies:

- Comparable regional climate change data was lacking. Climate change projections referred to different models or time horizons, and the data quality varied. Time-dependent analyses were not possible.

[3] iModeler is a web-based cause-effect model which allows to analyse interrelationships and interactions of an infinite number of influencing factors and weighting of the connections between factors. The freeware version is available online: https://www.consideo.de/imodeler.html.

- It was not possible to rank the severity of identified interrelationships between climate stimuli/direct climate impacts and environmental impacts or supply risks as they were assessed on the base of qualitative case studies. Therefore, the iModeler weighting function could not be used on a representative basis.

In conclusion, the modelling helped to map the results of the case studies and to develop a systematic assessment of these results. In addition to using iModeler as a descriptive tool, the team discussed the option of developing a generic model.

Such a model would not need to be fact-based to overcome the aforementioned data limitations; indeed, it could be used in an explorative way to systematically assess climate change impacts on mining activities and the environment in a broader, more general context. A generic model would also take into account economic implications (market demand, price development, jobs), and cross linkages between environmental categories, causal loops and adaptation measures already in place such as flood management or adapting waste management.

Such a non-fact based and generic model could be developed, for example, in the context of a modelling workshop conducted by iModeler experts together with scientists from the relevant subject areas.

2.1.4 Overall assessment grids and identification of overall observations

Since it was not possible to further model the results of the site-specific assessment grids in iModeler, we summarised the results in several overall assessment grids. This process was carried out by transferring the results of the assessment matrixes for the case studies to overall assessment grids. This allowed us to systematically map frequencies of identified "negative climate impacts" in the environmental categories and for potential interruptions of supply.

As these frequencies are based on our specific case studies, no quantitative results on global climate change impacts on mining can be derived from the overall assessment grids. However, the patterns that became apparent in the grids served as starting points to identify main observations on climate change impacts on environmental impacts and supply. We compiled these observations in an input paper that was discussed and complemented together with experts at a workshop held in November 2018.

2.2 Overall findings and observations from case studies

Two of the central research questions for the project were: *How are environmental risks of mining impacted by climate change? How are raw material supply chains affected?* The overall findings and observations discussed in this chapter provide the answers. The findings and observations are mainly based on interrelationships described as "negative potential climate impacts" in overall assessment grids. In addition, this chapter addresses climate change impacts on mining communities and potential positive climate change impacts. We include examples from the case studies and beyond in order to illustrate the identified potential impacts.

2.2.1 Extreme weather events as main risk

The case studies show that the impacts of extreme weather events, such as heavy winds, tropical cyclones and heavy rain, stand out as the main risk in terms of environmental impacts and disruption of supply chains across different raw materials, mining sites and climatic zones. For example, flooding, caused by heavy rain or surges, poses dangerous risks, especially with regard to hazardous or toxic waste storage (spillover, dam failure), fresh water supply and rehabilitation. It may lead to disruptions of operation. Drought poses dangerous risks, especially with regard to water use, as during a drought less water is available for dust suppression, ecosystems or local communities. Having less water available for dust control may also affect the work force and lead to disruptions of operation.

Combination or sequence of extreme events as special case

A combination or sequence of extreme events can increase risks; for example, an extreme wet weather event during a period of prolonged drought can increase the risk of environmental impacts of mining and processing operations. This is the case for the Mount Whaleback iron ore mine in Australia, which is situated in a region projected to face more intense droughts as well as an increased intensity of rainfalls and cyclones. Water loss by evaporation during drought events can lead to the development of hypersaline water bodies. In the case of the Goonyella Riverside coking coal mine in Australia, the risk of acid mine drainage is higher during drought events and high evaporation losses, when water infill of pits is used to prevent the generation of acid mine water. In both cases, the risk for harmful saline and/or acid drainage is considerably higher if extreme rainfall occurs in combination with drought.

Tailing dams and slurry ponds in particular are highly vulnerable to climate change risks. Many tailing dam failures have occurred after torrential rains (Rico et al., 2008). Exemplary cases are the failure of the Ok Tedi dams system, Papua New Guinea (1984)[4], and the one in Baia Mare, Romania (2000)[5]. In addition, acid mine and/or rock drainage collection systems, like treatment plants for mines during operation and after closure, are generally designed with certain maximum flows in mind. These limits may be exceeded in the case of extreme weather events, causing spillovers, thereby releasing untreated, heavy metal polluted waters to the environment.

Large open pit mines can also be affected by extreme weather events such as heavy rain and consequent flooding, leading to high pumping costs or even disruption of production if deeper work areas flood. Larger open cuts will have to adjust to extreme precipitations. As energy costs are high, dewatering and/or drainage pumps are generally designed (in terms of capacity) in such a way that they work at optimum load. Therefore, their adaptation ability to flooding is limited, and additional stand-by pumps are required.

Diverse impacts of flooding

Flooding is defined as the “overflowing of the normal confines of a stream or other body of water, or the accumulation of water over areas not normally submerged” (IPCC, 2014). Flooding can be caused by heavy rain, storm surges, sea level rise. In our research, we made no distinction between freshwater and saltwater flooding. A summary from the case studies shows how flooding can harm the environment at mining and processing sites and disrupt supply chains:

[4] Ok Tedi is a gold and copper mine, which has disposed more than two billion tons of contaminated material in the rivers Ok Tedi and Fly since production began in 1984. To date, more than 2 000 km^2 of floodplain have been destroyed (Seib, 2016). Kirsch (1996) notes, that heavy rainfall swept the tailings into the rain forest, swamps and creeks, and led to about 30 km^2 of dead forest. The United Nations Environment Programme (2007) noted that the Ok Tedi mine site is responsible for uncontrolled discharge of 70 million tons of waste and mine tailings annually. Consequences were raising riverbeds and causing flooding, sediment deposition and damage to the local rain forest.

[5] After a sequence of extreme weather events, the tailings of the Baia Mare gold mine overflowed and tore a 25 m long gap in the embankment wall. 100 000 m^3 of tailing sludge (containing heavy metals) and water containing around 120 tons of cyanide got into local waterways down to the Danube (Baia Mare Task Force, 2000).

Water use: Flooding can negatively affect freshwater availability (e.g. brackish water from tin mining in Indonesia), and flooding due to sea level rise may induce salt-water intrusion of water containment systems (e.g. nickel mining in Canada).

Waste: Flooding can lead to the uncontrolled release of metal contaminated effluent or to physical destruction due to overspills (identified potential impact in seven out of the nine case studies).

Rehabilitation: Flooding can hamper rehabilitation efforts (identified in all case studies, except lithium mining in Chile due to mining from brines).

Biodiversity: Flooding can harm biodiversity, which is already under pressure from mining operations.

Supply: Flooding of the mining pit, transport routes, processing facilities, or ports may (at least temporarily) disrupt the supply in nearly all cases; in addition, workers are put at risk.

Moreover, extreme weather events put a number of specific mining operations at risk, such as heap-leaching operations (which are dependent on predictable weather conditions), salt evaporation plants (including lithium brine exploitations), and shore-based alluvial operations in rivers (dredges are generally floating devices and can cope with water level rises, as long as the draft of the river does not surpass critical levels). Open casts in sediments, meanwhile, may suffer from instability of slopes if the drainage system is insufficient or the precipitation too high.

However, when assessing the risks posed by extreme weather events it is important to look at not only the type but also the scale of mining operations. The experts at the workshop agreed that it is necessary to differentiate between artisanal/small-scale mining (ASM) and industrialised, large-scale mining (LSM).

In the context of this project, ASM was only prevalent in the case study on Indonesia (tin mining). Although it was difficult to assign specific climate change-induced environmental risks to ASM and LSM in the case study, the vulnerability to different climate impacts varies between both sectors because ASM often does not have sufficient adaptive capacities. This has do with:

- the lack of mechanisation
- the usage of rudimentary techniques
- low occupational health and safety (OHS) practices
- the lack of a skilled workforce
- the lack of social security
- the lack of awareness about EHS issues

(IGF, 2017).

The Indonesia case study showed that extreme weather events – particularly heat waves, floods and landslides – could put the tin miners' health at risk. While this could also affect LSM workers, this is especially true for workers in ASM as their working conditions are often precarious and dangerous.

Another aspect to consider is the extent of vulnerability of different climate regions and/or vegetation zones. For example, forests, especially mangroves, strengthen the resilience of ecosystems. However, both increasing extreme weather events and mining contribute to deforestation and thus potentially further reduce the resilience of sites.

Discussions during the expert workshop indicated that researchers need to further assess the finding that "extreme events are the main risk for mining" – indeed, the comparability between the two groups (sudden- and slow-onset) is more complex than it seems at first sight. One reason for the finding could be that short-term impacts are generally better known than long-term, slow-onset impacts.

2.2.2 Climate change and environmental risk of mining

The following chapter presents short definitions of selected environmental categories and summarises the main findings regarding the potential impacts of climate change.

2.2.2.1 Land use

This category describes the area of land consumption for mining and processing activities. Open pit mining with large overburden and tailings deposition facilities has a significant land footprint. In general, climate impacts do not change land consumption since the size of the mining pit and tailings is generally not affected by climatic changes. However, in mining areas where changes of topsoil and vegetation cover already cause degradation, sedimentation and flooding, an increasing risk of erosion/landslides and flooding can additionally contribute to land degradation, as for example in the case study on tin mining in Indonesia. This is due to bucket-line dredging of placer tin deposits, which removes the topsoil of large areas.

In addition, climate change might lead to an increase in land use if mining companies abandon e.g. flooded sites and move operations to other pits or open new mining projects at other locations to diversify their operations. In this way, if production at one site is reduced due to flooding, production can be increased at another, unaffected site. As pointed out at the expert workshop, the shifting of operations to alternative locations due to climate change can be observed in other sectors (e.g. in agriculture).

In contrast, we do not expect an increase of land use due to the building of more shallow dams for dam safety. Instead, dam safety will be achieved by switching to other dam construction types that more expensive (e.g. concrete dams instead of large upstream soil compacted dams). As energy demand increases and mine might switch to renewables like solar or waterpower to reduce GHG emissions, the land use related to energy production might also increase.

2.2.2.2 Energy use

Energy use depends on the raw material sourced and the processes used for extraction and treatment. When it comes to mining, diesel fuel and electricity are the main required energy sources. Based on the case studies, we did not identify direct climate change-induced impacts on energy use. However, some indirect impacts could be detected. For example, increasing water scarcity may increase energy demand (desalination, increased on-site water pumping).

Today, energy is important for industrial mining operations, and supply shortages are one of the major bottlenecks for expansion. In the future, energy demand is expected to increase, not only because of potentially increasing water scarcity but also due to mining of lower ore grades. Nevertheless, there is potential to reduce the specific energy demand of mines. New and more efficient technologies can be applied, especially for milling, which uses a lot of energy in processing (Harder, 2017).

2.2.2.3 Water use and dust emission

The category water use describes the use of water for mining and processing. Two important parameters are the total amount of water used and the water availability in the mining area/region. Water use is mostly affected by drought, not only in arid regions but also in regions with a significant dry period (e.g. Australia, Weipa/bauxite). Additionally, analysis of the case studies shows that flooding and erosion/landslides affect water use. In mining, water is primarily used for processing and for dust suppression. The water used for energy generation is another pertinent aspect.

The most relevant aspect identified across the analysed sites is "less water availability for dust control". In addition, flooding and erosion/landslides may affect water containment or water reservoir systems (e.g. Canada, nickel and Indonesia, tin) leading to reduced freshwater availability. The competition for water is expected to increase, particularly in places where different user groups, such as agriculture, industry, or domestic use have limited water access (e.g. South Africa, PGMs/nickel).

The experts at the workshop considered droughts, especially those occurring erratically, a major cause of a potential increase of competition over water with local communities and other sectors. Water storage could be an adaptation measure, but this is itself potentially at risk in times of flooding and increasing risks of erosion/landslide. A series or combination of rainfall events and droughts causes additional difficulties. In general, it is a problem when usual rainfall patterns do not apply any longer and the predictability of changing events becomes more difficult.

To reduce the competition in water-poor regions, water losses can be minimised by recycling processed water, or storing tailings from the concentration plant on dry stockpiles after solid-liquid separation of the slurry in decanting or pusher centrifuges or filter presses. This innovation is increasingly applied in Andean desert environments (i.e. using technology from Hiller[6]/Ferrum or Andritz) where water is extremely scarce and expensive and losses due to evaporation from tailings ponds are too costly. This also increases tailing management facility safety. Evaporation can also be reduced by covering ponds with white light-reflecting floating devices.

Water management in mining and processing

Our case studies identified the reduced availability of water for dust control as an important challenge regarding climate change impacts on water use. Water use for wetting roads can vary between 0% and 15% of total water consumption according to Cochilco (2008). The amount of fresh water used could be reduced by using low-quality water. In general, water use in mining operations is oriented towards the availability of natural water sources. Where water is available in abundance, there is no recycling; where water is scarce, it is treated and reservoirs are built or water is even transported over large distances and heights to the mine site (e.g. desalinated marine water for copper mining in Chile).

[6] In recent years together with mining companies from Bolivia and Chile, Hiller has been piloting these systems in the framework of a DEG supported public private partnership project (DEG is a subsidiary of KfW).

Limited water availability can be a problem, but excess water is also problematic, e.g. when water levels need to be lowered or water needs to be pumped out for access. Water demand in mining is mainly relevant for processing, especially for most of the separation processes (hydro-gravimetrical, flotation, leaching, amalgamation etc.). The minerals with a higher water demand for processing are usually low grade due to geochemistry and mineralogy. The finer the intergrowth of ore minerals and the finer the ore that needs to be milled, the larger the amount of water required. When ore deposits are located in water scarce areas, processing is sometimes relocated to areas where more water is available.

2.2.2.4 Biodiversity and rehabilitation

The International Council on Mining & Metals (ICMM) defines land rehabilitation as "the return of disturbed land to a stable and productive condition" (ICMM, n.d.). Rehabilitation and biodiversity are closely interrelated, and accordingly the negative potential climate impacts that were identified across sites in the case studies account for both categories.

Mining and processing often affect biodiversity or ecosystems, including through the degradation of soil, waterways, vegetation and habitat of animals. During and at the end of mining operation, rehabilitation helps return mined sites to stable and functioning ecosystems, ideally following rehabilitation plans. Rehabilitation is affected by nearly all climate impacts in all case studies. All indicated climate stimuli and direct climate impacts potentially impede revegetation and rehabilitation measures at mining sites, e.g. temperature increase, precipitation change and extreme weather events. In addition, rehabilitation extends into a timeframe when climate change impacts are projected to be even more pronounced than in the nearer future (Stratos, 2011).

Both biodiversity and rehabilitation are especially affected in regions that regularly face extreme weather events and are situated in countries with weak governance (as law enforcement and environmental monitoring are weaker).

2.2.3 Climate change and disruptions of mining operations

In addition to the climate change impacts on environmental risks of mining, we also identified impacts on mining operations that may affect security of supply. According to our analysis of the case studies, flooding, erosion/landslides and heavy winds are the most dangerous risks in terms of damaging sites and transport routes and putting workers at risk. Moreover, fires, drought (due to less water being available for dust suppression or the water supply being reduced or interrupted by water use restrictions or a shortage) and heat waves endanger the workforce, potentially leading to lower production levels.

Case study examples: Past weather extremes

Temporary disruptions of operations due to extreme weather events already happen frequently. For example, bauxite mining in Weipa, Australia, was interrupted due to weather impacts on operations in 2016, which was the main cause for a production decrease by 7% compared to the previous year (Rio Tinto Group, 2017). Several coal-mining operations in Queensland, Australia, were severely affected by floods in 2010-2011 and 2017. The 2010-11 floods affected 85 per cent of Queensland's coal mines, reducing production or leading to the closure of mines. The mines needed several months to fully recover (Queensland Flood Commission of Inquiry 2012). The export disruptions led to increased coal prices (White, 2010). And in March 2017, Cyclone Debbie damaged the railway system delivering coal to the ports, leading to a significantly reduced rail capacity (BHP Billiton, 2017). Railway operators needed up to four weeks to reopen (Aurizon, 2017).

In Indonesia, in 2016, flooding on Bangka Island led to limited access to tin smelters and mining sites, and the operator PT Timah shut one mining site during the flooding (ITRI, 2016).

In Canada, tungsten mining at the Cantung mining site was severely affected in 2012 when extreme weather events led to mudslides and washouts and North American Tungsten had to stop its operations for about a week due to food and fuel shortages (Tobin, 2012).

Although these incidents are local and do not always affect global supply, they are expected to increase due to climate change, both in frequency and geographic distribution.

Potential supply chain disruptions are especially likely to occur when mining takes place in regions with potential increases of flooding, erosion/landslide and heavy wind. In addition, regions with potential increases of drought, fires and heat waves may be affected by temporary supply chain disruptions. Furthermore, mining sites in remote areas are more vulnerable to potential supply chain disruptions, especially because of the long transportation distances through sparsely populated or uninhabited areas.

Slow or long-term changes such as temperature increases and changes in precipitation are not expected to directly increase the risk of physical supply chain disruptions, but temperature and precipitation changes can have indirect impacts. With regard to transport routes, both negative and positive impacts are possible: land-based transport routes in permafrost regions are exposed to risks from melting permafrost, including road slope instability and accelerated erosion. By contrast, melting sea ice potentially offers new alternative transport routes. In general, land-based transport routes via roads have a higher flexibility than rail-bound transports.

Extreme weather events are known to cause damage to infrastructure for mining, processing and transport. In contrast, slow-onset stimuli and direct climate impacts are harder to identify for producers and researchers due to the lack of past experiences. However, slow, gradual changes can affect temperature-sensitive, and some slow-onset aspects are more predictable. For example, some mining areas in the Andes of Peru, Bolivia and Chile depend on water sources fed by glaciers that are retreating due to climate change, forcing mines to consider adaptation strategies. In the short term, increased melting leads to higher drainage of the glaciers (water supply, but risk of flooding), but in the long term, the water supply will shrink or even stop completely.

Demand for equipment: supply dependencies of mines

Supply chains are not only directed from mine to market. A mine itself also depends on certain supplies for running operations: power (mines connected to the central grid), fuel and working materials are essential for operation. Any disruption of these flows can hamper production as well as interfere with transport routes needed for the delivery of mining products to markets.

2.2.4 Climate change and mining communities

In addition to environmental risks and supply disruptions, we also identified potential social impacts. Communities in the vicinity of mines or production sites are often under pressure from multiple stressors, with mining being one stressor among several. For example, the

Mogalakwena mine operates in an area characterised by high social inequality and water stress. Local communities are dissatisfied with poor basic services and infrastructure in the region. In addition, these communities report that they suffer from environmental impacts such as noise, air pollution and water contamination caused by mining operations and have experienced resettlements. Climate change can act as a 'risk multiplier' in such contexts: this means that it can exacerbate already existing social and/or environmental impacts and increase the risks of tensions and conflicts. For example, increasing water stress linked to climate change could intensify competition over water between the mine and the communities in the future.

2.2.5 Are there positive climate change-induced impacts?

A small number of case studies showed potentially positive impacts with regard to the production process and the supply chain. For example, sea routes in arctic and/or permafrost regions could potentially be expanded in the case of sea ice change. And lithium mining from brines might benefit from increasing temperatures, which could result in a faster evaporation of the brines. In this case, land use could potentially be reduced because smaller evaporation ponds would function more effectively.

However, new supply routes may require negotiations with locals and authorities. In the case of the nickel mine Voisey's Bay in northern Canada, sea ice change could open up new shipping routes or prolong the shipping season. However, the local indigenous community would have to agree to new shipping routes and a prolonged shipping season as the current agreement between the mine and the community would need to be modified. In the case of lithium mining in the Chilean Atacama desert, solar evaporation from ponds may not be further accelerated if the humidity level is already very low. These examples clearly show that potentially positive impacts need to be closely assessed. The consequences are very specific and depend on the local situation.

2.3 Linkages between environmental categories and environmental hazard potentials (EHP)

Most industrialised economies depend on the import of raw materials. Criticality assessments seek to respond to concerns about inadequate supplies of materials by determining the availability of minerals and metals important to an economy. There are various concepts for how to evaluate criticality. Most raw material criticality assessments only include environmental aspects to a limited extent. The OekoRess project, also commissioned by the German Environment Agency, aims at closing this gap and has introduced the concept of environmental criticality (Dehoust et al., 2017). Environmental criticality has two dimensions: the environmental hazard potential (EHP) of raw materials from mining, and the dependency of products, industries and economies on individual raw materials. The centrepiece of OekoRess was to develop a method to quantify the EHPs of mined raw materials and mining projects. A set of raw material- and site-related indicators derived from environmental goals represent the EHPs relevant for mining. These not only include criteria for environmental hazards of mining operations, but also take into account the socio-political context of mining in order to assess the probability that effective countermeasures are taken to avoid environmental damage.

The follow-up project OekoRess II applied this method and produced about 50 raw material profiles with EHP results for the full set of raw material specific indicators. In addition, the team developed an aggregated EHP-score for each raw material, which allowed them to rank the overall EHPs of the evaluated raw materials. Raw materials with a very high EHP have a higher likelihood of severe environmental shortcomings in mineral supply chains, especially when mined in countries with weak governance.

The EHP results for geological and technological indicators as well as for value chain indicators (energy demand and material demand) are dependent on the characteristics of a given raw material and its extraction and processing types (e.g. geological conditions of a raw material, mining type and global cumulated energy demand), irrespective of its production countries. In contrast to the EHP for these indicators, the EHP result for the governance indicator takes into account the respective production share of countries; the natural environment indicators are also dependent on the production countries as well as on the location of the specific mining sites. These results are based on production data from 2014.

In contrast to the assessment based on past data, the KlimRess project focuses on the changing conditions in the future due to climate change. Due to the different reference points, it is interesting to compare both approaches and explore possibilities for adapting this method and identifying opportunities to link the results.

Climate change-related risks are not part of the OekoRess method to evaluate environmental criticality. The project team assessed options on how to include this project's findings into the OekoRess approach. In a first step, the environmental categories used in this project were compared with the goals and indicators for the assessment of EHPs in the OekoRess context (Table 3).

Table 3: Mapping KlimRess environmental categories with OekoRess indicators (EHPs)

Environmental category		Raw material- and site-related indicators to assess EHPs	
Category	**Description**	**Goal**	**Indicator**
Land use	Land area used for mining and refining processes and impacts on land used	Limiting the direct impacts on ecosystems Site-related additionally: Limiting the direct impacts on ecosystems	Technology: Mine type (underground, open pit, sediment) Geology: Deposit size (total metal content of deposit: small, medium, large)
Water use	Water availability in the region and water demand of the mining & refining processes	Avoiding competition in water usage	Natural Environment: Water Stress Index (WSI) & desert areas (GIS assessment)
Energy use	Energy use of the mining & refining processes	Limiting the global extent of EHPs Site-related: Limiting the effort for exploitation	Cumulated energy demand of global production (CED_{global})[7] Geology: Ore grade (average ore grade of deposit: rich, medium, poor)

[7] CED and CRD_{global} are value chain indicators, the specific values for CED and CRD represent the cumulated demand from mining, processing and raw material production.

Waste	Production of residual waste and process residues (amount, toxicity, ...) and	Avoiding pollution risks	Technology: Use of auxiliary substances (use of auxiliary and/or toxic chemicals)
	Waste disposal and waste management	Limiting the global extent of EHPs	Cumulated raw material demand of global production (CRD_{global})[8]
		Site-related: Minimisation of risks from mining waste	Technology: Mining waste management (safe storage/stable waste heaps/risky deposition, unstable tailing ponds, no management)
Emissions	Air, water emissions	Avoiding pollution risks	Geology: (1) preconditions for acid mine drainage (geochemical bond); (2) paragenesis with heavy metals (heavy metal concentrations) (3) paragenesis with radioactive components (uranium, thorium concentrations)
	GHG emissions, noise, light emissions	-	-
Rehabilitation	Mine closure plans and financing of mine closure and rehabilitation	Site-related: Minimisation of longevity of impacts	Technology: Remediation measures (process-parallel, financial accruals for rehabilitation, no provision)
	Revegetation		
Biodiversity	Flora and fauna	Site-related: Minimisation of longevity of impacts	Technology: Remediation measures (process-parallel, financial accruals for rehabilitation, no provision)
	Protected areas	Protection of valuable ecosystems	Natural Environment: Protected areas & Alliance for Zero Extinction (AZE) sites (GIS assessment)
Health	Health issues arising from mining/processing for workers and/or local communities	Compliance with standards	Environmental governance in major production countries
		Site-related: avoiding environment-related conflicts in resource usage	Conflict potential with local population (two Worldwide Governance Indicators)

Source: Own table, based on project results and Dehoust et al. (2017)

The comparison of the environmental categories and the goals and indicators for the assessment of EHPs showed that most of the environmental categories do have equivalents in the different environmental goals and thus also in the OekoRess indicators. These connections are essential, and further interrelationships were assessed on this basis.

2.3.1 Dependencies between indicators regarding climate change

In order to identify potential links between the methodologies of both projects, it is necessary to understand the nature of the OekoRess indicators. The team screened the OekoRess indicators and selected the ones that are potentially impacted by climate change (see Table 4). The strongest link between climate change impacts and the OekoRess goals and indicators is the influence of climate change on natural accident hazards. In particular, flooding, tropical storms and landslides are indicators with direct connections to climate change. Earthquake hazards, on the other hand, have to be considered separately as they are a tectonic phenomenon.

Table 4: Potential climate change impacts and OekoRess EHP goals and indicators

Raw material- and site-related indicators to assess EHPs		Potential impacts due to climate change
Goal	**Indicator**	
Avoiding natural accident hazards	Natural accident hazards (flooding, storms, landslide)	Direct connections between EHPs and climate change impacts, e.g. stronger and more common heavy rain events, more intense storms or landslides.
Avoiding competition in water usage	Natural Environment: Water Stress Index (WSI) & desert areas	More stress on water availability due to heat waves, dry periods, but also desertification processes, more water demand of mining companies for dust suppression or further process steps.
Limiting the global extent of EHPs	Cumulated energy demand of global production (CEDglobal)	More energy demand for mining companies due to higher temperature and workers safety, more energy for water supply.
Minimisation of risks from mining waste	Technology: Mining waste management	Risk of losing stability of tailing dams by more intense heavy rain events, longer periods of drought and impacts on soil.
Minimisation of longevity of impacts	Technology: Remediation measures	Harsher conditions for remediation measures due to climatic changes, e.g. change in humidity of the soil, longer dry periods.
Environment-related conflicts in resource usage	Conflict potential with local population	Higher water usage and conflicts in case of higher water demand from mining companies.

Source: Own table, based on project results and Dehoust et al. (2017)

Not every OekoRess indicator is influenced by anthropogenic climate change.[8] For example, indicators addressing the geology of rocks and the associated relationships, such as preconditions for AMD or paragenesis with heavy metals, are predominantly determined by long-lasting processes of rock formation or are consequences of mineral composition. In addition, indicators referring to specific mining and processing technologies like the use of auxiliary substances are not directly influenced by climate change. A complete overview of the OekoRess indicators is given in Appendix B, Table 26 and Table 27.

Despite the connections shown between climate change and the OekoRess EHPs in Table 3 and Table 4, the in-depth comparison of the evaluation results from the case studies in KlimRess and

[8] Anthropogenic climate change refers to historical time periods of human civilizations and to not geological dimensions (origin and evolution of the Earth). Different climate surroundings of course do have an impact on the geology of rocks, but only in a very long-term perspective.

the raw material-related evaluation of the nine raw materials indicated no clear relationships between certain climate change impacts and raw material specific EHPs.

2.3.2 Further developing the OekoRess approach

The previous sections showed some linkages between the climate change impacts analysed in this project and the EHPs from OekoRess. However, it is neither advisable to include climate change implications in the existing OekoRess indicators (i.e. to establish new criteria for the measurement of e.g. waste management that also include climate change adaptation measures), nor practicable to replace the current indicators with new indicators that also account for climate change.

Nevertheless, one feasible option to incorporate climate change into the OekoRess methods would be to add an additional indicator in line with those EHP indicators that are also related to production countries and mining sites. Such an indicator could indicate to what extent a raw material is affected by climate change depending on the production countries or mining sites. The following chapters show how the vulnerability of raw materials to climate change could be assessed.

3 Climate change vulnerability assessment of main producing countries and reserves

As the findings and observations from the case studies indicate, climate change is projected to adversely affect mining operations around the world, in many cases exacerbating environmental risks at mining and processing sites as well as disrupting supply chains. The case studies show what kind of climate change impacts can occur along the mining supply chain. However, they did not allow us to draw more general conclusions as to which countries and thus also which raw materials (in terms of their production and supply) will be particularly affected by climate change.

Some raw material-producing countries are more vulnerable to the adverse impacts of climate change than others because they are more exposed to weather and climate hazards or less capable of adapting to climatic changes. Therefore, we posed the following research questions*: Which raw material-producing countries are comparatively more at risk from climate change? What conclusions can be drawn about the global primary production of certain raw materials and their vulnerability to climate change? How might these risks change in the future?*

3.1 Approach based on projections for climatic zones

The initial idea was to approach this question by grouping mining regions based on climatic zones and assessing how these climatic zones are projected to change in the future. The most frequently used classification of climatic zones is the Köppen-Geiger climate classification (Kottek et al., 2006). This spatial climate classification represents long-term mean climate conditions based on historic temperature and precipitation observations, corresponding to five vegetation groups (Peel et al., 2007; Kottek et al., 2006).

Projected climate shifts of the Köppen-Geiger climate classification are available (Rubel and Kottek, 2010). Recent research has used this approach for global nickel, copper and lead-zinc resources (Northey et al., 2017). Northey et al. (2017) assessed global nickel, copper and lead-zinc datasets against the Köppen-Geiger classification for the observed period of 1951 to 2000 and for projections for 2100. The results show that 27 to 32% of copper, 17 to 29% of lead-zinc and 6 to 13% of nickel resources are in regions that are projected to experience major climate reclassifications, shifting from polar or snow climates to arid or warm temperate climates and from arid or warm temperate climates to equatorial climates (Northey et al., 2017).

Northey at al. (2017) deliver answers to the question of how climate zones of certain resources will be reclassified under climate change projections. However, we determined that this approach was not adequate for our research questions because climate zones only give a general idea of climate stimuli that are important at the site: e.g. permafrost degradation and sea ice change occur only in arctic/subarctic regions; water stress does not. Moreover, the projections for climate zones do not allow us to systematically understand climate change-related risks that are linked to specific weather and climatic phenomena and the governance situation:

- **Extreme weather events**: Extreme weather events are not part of the Köppen-Geiger classification. The specific climate zones, even the tropics, do not make it possible to draw conclusions about the occurrence of certain events, e.g. cyclones, hurricanes, and typhoons, in a given zone, and extreme precipitation is not bound to a certain climate zone. Even very arid regions can experience extreme precipitation events. The Köppen-Geiger climate classification thus cannot serve as a "weather and climate-related hazard inventory" for an area and does not indicate the exposure to climate changes.

- **Governance**: Weather and climate related hazards are not the only ones important for the assessment of climate impacts; the predisposition of communities or societies to suffer adverse impacts from hazards is also relevant. For example, while some communities or societies might be able to prepare for a cyclone, others do not have the capacity to do so. The Köppen-Geiger climate classification does not indicate the sensitivity and the adaptive capacity of communities or societies.

In order to include these considerations, we chose to conduct an indicator-based climate change vulnerability assessment instead.

3.2 Applied methodological approach

We shortlisted four open source vulnerability indices based on Leiter et al. (2017): the ND-GAIN Country Index, the Global Climate Risk Index, the INFORM Index for Risk Management and the World Risk Index. Both the INFORM Index for Risk Management[9] and the World Risk Index[10] include not only climate-related risks but also geo-physical risks (earthquakes and tsunamis). Their scope is therefore too broad for an assessment of a country's vulnerability to climate change. Germanwatch's Global Climate Risk Index focuses on weather-related natural disasters, but it is based on past data on direct losses and fatalities linked to those events. It does not include projections for future climate impacts. By contrast, the ND-GAIN Country Index (short: ND-GAIN, developed by the Notre Dame Global Adaptation Initiative hosted at the University of Notre Dame) comprises a set of indicators that also include climate change projections. Based on these considerations, ND-GAIN proved to be the most suitable to answer our research question.

ND-GAIN measures climate change vulnerability based on a country's exposure, sensitivity and adaptive capacity, as well as its readiness to "leverage private and public sector investment for adaptive actions" (Chen et al., 2015: 2). As our research is directed towards questions of vulnerability, we did not include readiness in our assessment, instead focusing on the vulnerability aspect of ND-GAIN.

ND-GAIN defines vulnerability as the "propensity or predisposition of human societies to be negatively impacted by climate hazards" (Chen et al. 2015: 3). The three variables that determine vulnerability are defined in the following way:

- **Exposure**: "The extent to which human society and its supporting sectors are stressed by the future changing climate conditions. Exposure in ND-GAIN captures the physical factors external to the system that contribute to vulnerability" (Chen et al. 2015: 3). The exposure score answers the question: how exposed is a country to weather and climate hazards? The least exposed country according to ND-GAIN is Andorra (exposure score: 0.247), while the most exposed is the Maldives (exposure score: 0.722).
- **Sensitivity**: "The degree to which people and the sectors they depend upon are affected by climate related perturbations. The factors increasing sensitivity include the degree of

[9] The INFORM Index for Risk Management is a collaborative project of the Inter-Agency Standing Committee and the European Commission.

[10] The last report of the World Risk Index was published by Bündnis Entwicklung Hilft and Ruhr University Bochum.

dependency on sectors that are climate-sensitive and proportion of populations sensitive to climate hazard due to factors such as topography and demography" (Chen et al. 2015: 3-4). The sensitivity score answers the question: how climate-sensitive are a country's sectors and population? The least sensitive country in the ranking is Australia (sensitivity score: 0.119); the most sensitive one is Guinea-Bissau (sensitivity score: 0.618).

- **Adaptive capacity**: "The ability of society and its supporting sectors to adjust to reduce potential damage and to respond to the negative consequences of climate events. In ND-GAIN adaptive capacity indicators seek to capture a collection of means, readily deployable to deal with sector-specific climate change impacts" (Chen et al. 2015: 4). The adaptive capacity score answers the question: how capable is a country of adapting to climate change? Italy has the strongest adaptive capacity in the ranking (adaptive capacity score: 0.175); Somalia is last in the ranking (adaptive capacity score: 0.877).

For each variable, we created four score groups (see Table 5) in order to directly rank and compare the countries with significant production and reserves.

Table 5: ND-GAIN score groups

Score group	Overall vulnerability	Components of overall vulnerability		
		Exposure	Sensitivity	Adaptive Capacity
Low//strong ≤ 25% quantile	**Low**: 0.274-0.373	**Low**: 0.247-0.378	**Low**: 0.119-0.322	**Strong**: 0.175-0.379
Low-to-medium// strong-to-medium > 25% quantile and ≤ 50% quantile	**Low- to-medium**: 0.374-0.423	**Low-to-medium**: 0.379-0.442	**Low-to-medium**: 0.323-0.389	**Strong-to-medium**: 0.380-0.471
Medium-to-high// medium-to-weak > 50% quantile and ≤ 75% quantile	**Medium-to-high**: 0.424-0.520	**Medium-to-high**: 0.443-0.491	**Medium-to-high**: 0.390-0.470	**Medium-to-weak**: 0.472-0.618
High//weak > 75% quantile	**High**: 0.521-0.680	**High**: 0.492-0.722	**High**: 0.471-0.618	**Weak**: 0.619-0.877

Source: Categorisation developed in the project based on ND-GAIN (2018).

These score groups were created based on the quartiles of the entire range of a score per variable. This means, for example, that the group "low vulnerability" contains the 25 percent of all countries included in ND-GAIN with the lowest vulnerability score and thus represents the least vulnerable countries. We assigned the countries covered in this report to one of the four groups according to their respective score.

For the assessment of which raw materials from which producing countries are relatively more at risk from climate change, we focused on the nine minerals and metals selected in this project:

- Bauxite
- Coking coal
- Cooper
- Iron ore
- Lithium
- Nickel
- PGMs
- Tin
- Tungsten

We covered at least 75 percent of the current world production for each mineral and metal. In order to assess future risks, we focused on the countries with main reserves. Following the approach introduced by Coulomb et al. (2015), we assumed that the distribution of production might gradually converge towards the distribution of reserves.

3.3 Assessment results for nine raw materials

In the following sub-chapters, we present and discuss the climate change vulnerability assessment results for each of the raw materials in detail. For this report, we decided to focus on exposure and adaptive capacity as two components of vulnerability. Sensitivity is not discussed in detail; however, sensitivity scores are displayed in the tables. The presentation and discussion of results for each raw material are followed by a comparison of the vulnerability of producing countries and reserves for the nine raw materials. In addition, the importance of exposure and adaptive capacity for determining vulnerability is illustrated, showing the results for tin- and iron ore- producing countries and reserves as example.

3.3.1 Bauxite

Table 6: Main characteristics of bauxite production and reserves

Characteristics	Production	Reserves
Coverage of the climate change vulnerability assessment	6 countries (covering 86.55% of world production)	6 countries (covering 71.76% of world reserves)
Relative vulnerability in comparison to all other materials covered in the report[11]	2nd most vulnerable (of 9 raw materials covered)	Most vulnerable (of 9 raw materials covered)

Source: Results based on USGS (2018), ND-GAIN (2018).

Over 86 percent of bauxite production is located in six countries (Table 6). The market is currently dominated by Australia and China, which together account for over half of current world production (Table 7). While Australia is the top producer, Guinea has the largest reserves. Australia shows a higher exposure to weather and climate hazards than Guinea but also a much stronger adaptive capacity. Therefore, Australia's vulnerability is considerably lower than Guinea's (Guinea has the highest vulnerability score for bauxite producing countries). Vietnam has the third-largest reserves. The country's exposure is higher than Guinea's, but the adaptive capacity is stronger. Vietnam has medium-to-high vulnerability.

Table 7: Bauxite - Top Producing Countries and Reserves (2016) and corresponding ND-Gain scores

Country	Share of world production	Share of world reserves	Overall vulnerability	Components of overall vulnerability		
				Exposure	Sensitivity	Adaptive Capacity
Australia	29.82% (Rank 1)	20.00% (Rank 2)	0.294	0.480	0.119	0.273
China	23.64% (Rank 2)	3.33% (Rank 6)	0.389	0.448	0.324	0.394
Brazil	12.51% (Rank 3)	8.67% (Rank 4)	0.381	0.501	0.256	0.385
Guinea	11.45% (Rank 4)	24.67% (Rank 1)	0.537	0.436	0.403	0.729
India	8.69% (Rank 5)	2.77% (Rank 9)	0.497	0.572	0.383	0.536
Vietnam	0.44% (Rank 19)	12.33% (Rank 3)	0.475	0.491	0.451	0.482
Total[12]	86.55%	71.76%				

Source: Results based on USGS (2018), ND-GAIN (2018).

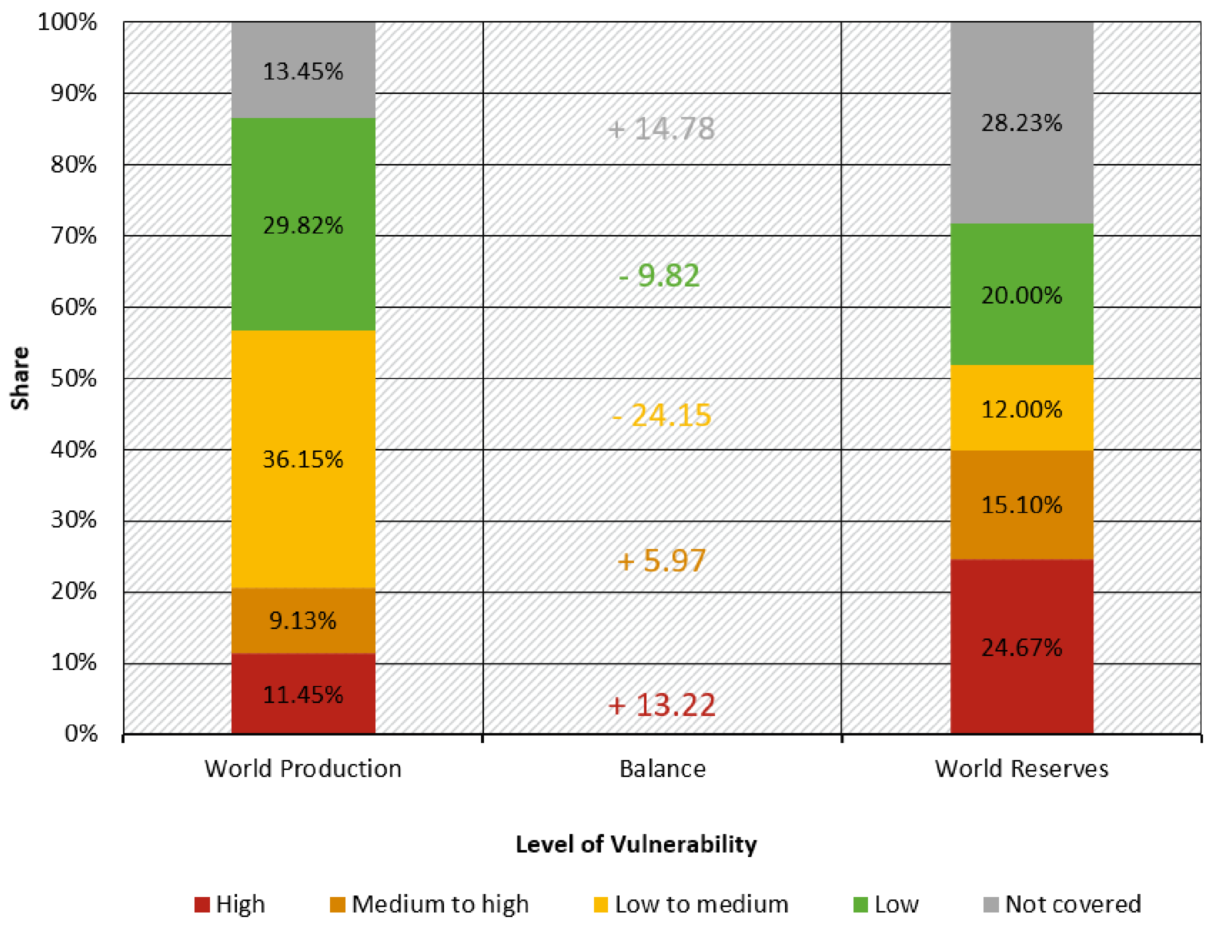
Comparing the total share of bauxite production and reserves, we can see that the share of reserves in countries with high vulnerability and medium-to-high vulnerability is larger than the share of reserves in countries with low-to-medium and low vulnerability (Figure 2). This is due

[11] See Figures 11 and 12 below.

[12] Without India and Vietnam, the value would be 77.42%.

to large reserves in the highly vulnerable country Guinea and the medium-to-highly vulnerable country Vietnam. The production of bauxite could therefore become more vulnerable in the future, increasing the risk of negative environmental impacts and supply disruptions.

Figure 2: Bauxite Production and Reserves - Vulnerability



Source: Own figure, results based on USGS (2018), ND-GAIN (2018).

3.3.2 Coking coal

Table 8: Main characteristics of coking coal production and reserves

Characteristics	Production	Reserves
Coverage of the climate change vulnerability assessment	5 countries (covering 90.27% of world production)	5 countries (covering 80.72% of world reserves)
Relative vulnerability in comparison to all other materials covered in the report[13]	7th most vulnerable (of 9 raw materials covered)	5th most vulnerable (of 9 raw materials covered)

[13] See Figures 11 and 12 below.

Source: Results based on USGS (2018), World Energy Council (2016), ND-GAIN (2018).

The global production of coking coal takes place in a few countries – over 90% of production is located in five countries (Table 8). Responsible for over 54% of current world production, China dominates the market for coking coal. Current and expected future production sites are, on average, concentrated in areas with comparably low vulnerability and strong adaptive capacity (Table 9).

Table 9: Coking Coal - Top Producing Countries and Reserves (2016) and corresponding ND-GAIN scores

Country	Share of world production	Share of world reserves[14]	Overall vulnerability	Components of overall vulnerability		
				Exposure	Sensitivity	Adaptive Capacity
China	54.67% (Rank 1)	17.76% (Rank 2)	0.389	0.448	0.324	0.394
Australia	17.48% (Rank 2)	8.89% (Rank 5)	0.294	0.480	0.119	0.273
Russia	7.74% (Rank 3)	9.97% (Rank 4)	0.335	0.440	0.203	0.360
India	5.69% (Rank 4)	12.25% (Rank 3)	0.497	0.572	0.383	0.536
USA	4.68% (Rank 5)	31.87% (Rank 1)	0.339	0.481	0.271	0.265
Total[15]	90.27%	80.72%				

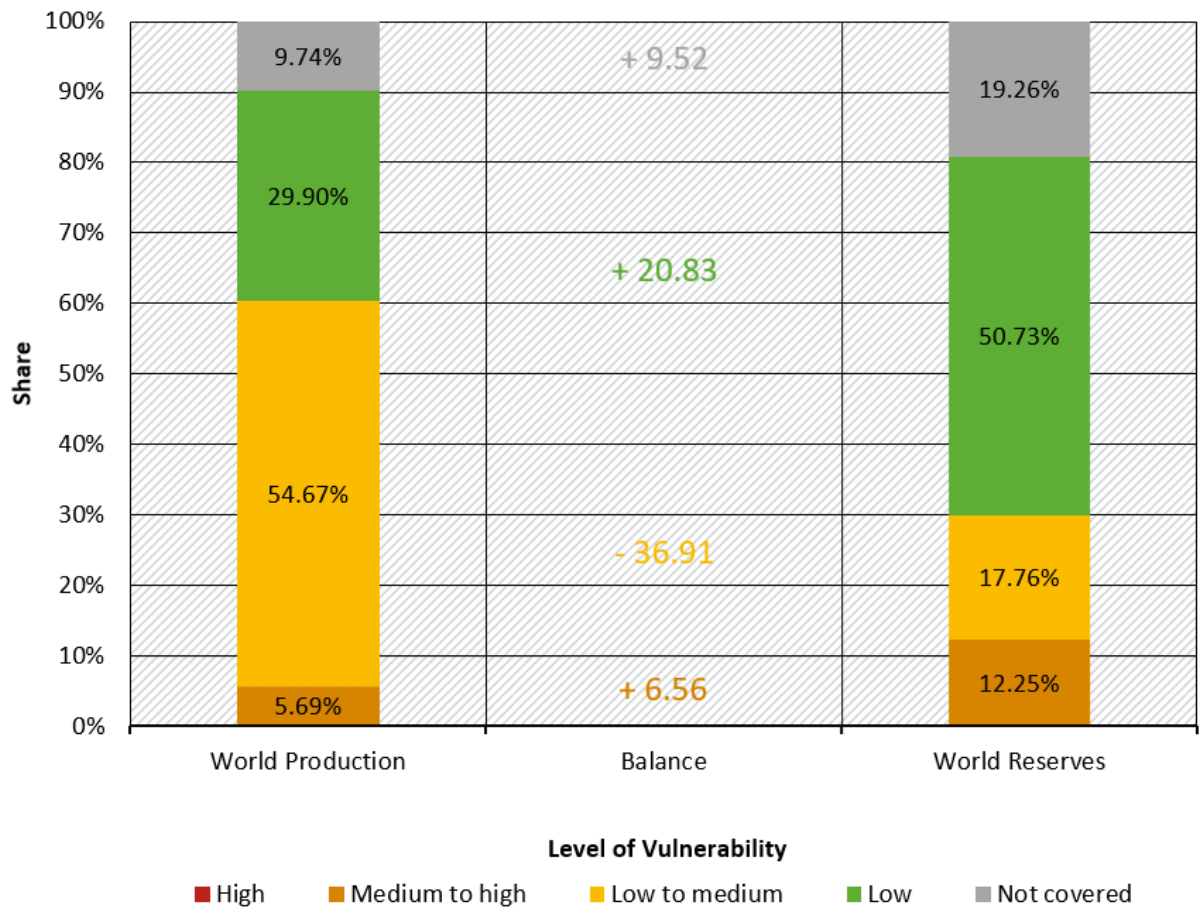
Source: Own figure, results based on USGS (2018), World Energy Council (2016), ND-GAIN (2018).

In general, the assessment shows a positive future trend as the USA holds 31.9% of world reserves and might therefore increase its production share, which would shift production to even less vulnerable production sites. Exposure, however, might slightly increase over time due to potential increases in India's production (India has the third largest reserves for coking coal) and its high level of exposure to climate change (Figure 3).

[14] As there is no data for coking coal reserves available, hard coal reserves for 2014 are listed.

[15] India and the USA were included because of their large reserves. The total without them would be 79.90%.

Figure 3: Coking Coal Production and Reserves – Vulnerability



Source: Own figure, results based on USGS (2018), World Energy Council (2016), ND-GAIN (2018).

3.3.3 Copper

Table 10: Main characteristics of copper production and reserves

Characteristics	Production	Reserves
Coverage of the climate change vulnerability assessment	9 countries (covering 75.95% of world production)	9 countries (covering 66.20% of world reserves)
Relative vulnerability in comparison to all other materials covered in the report[16]	3rd most vulnerable (of 9 raw materials covered)	2nd most vulnerable (of 9 raw materials covered)

Source: Results based on USGS (2018), ND-GAIN (2018).

Although Chile is by far the most important current producer of copper and home to the largest reserves, the production and reserves of copper are more dispersed than is the case for the

[16] See Figures 11 and 12 below.

other raw materials covered in this report (Table 10). Copper-producing countries show mixed vulnerability scores, ranging from Chile, USA and Australia, which have a low vulnerability, to the DRC and Zambia, which are highly vulnerable to climate change (Table 11). As is the case for most raw materials covered in this report, copper-producing countries exhibit high levels of exposure to climate change.

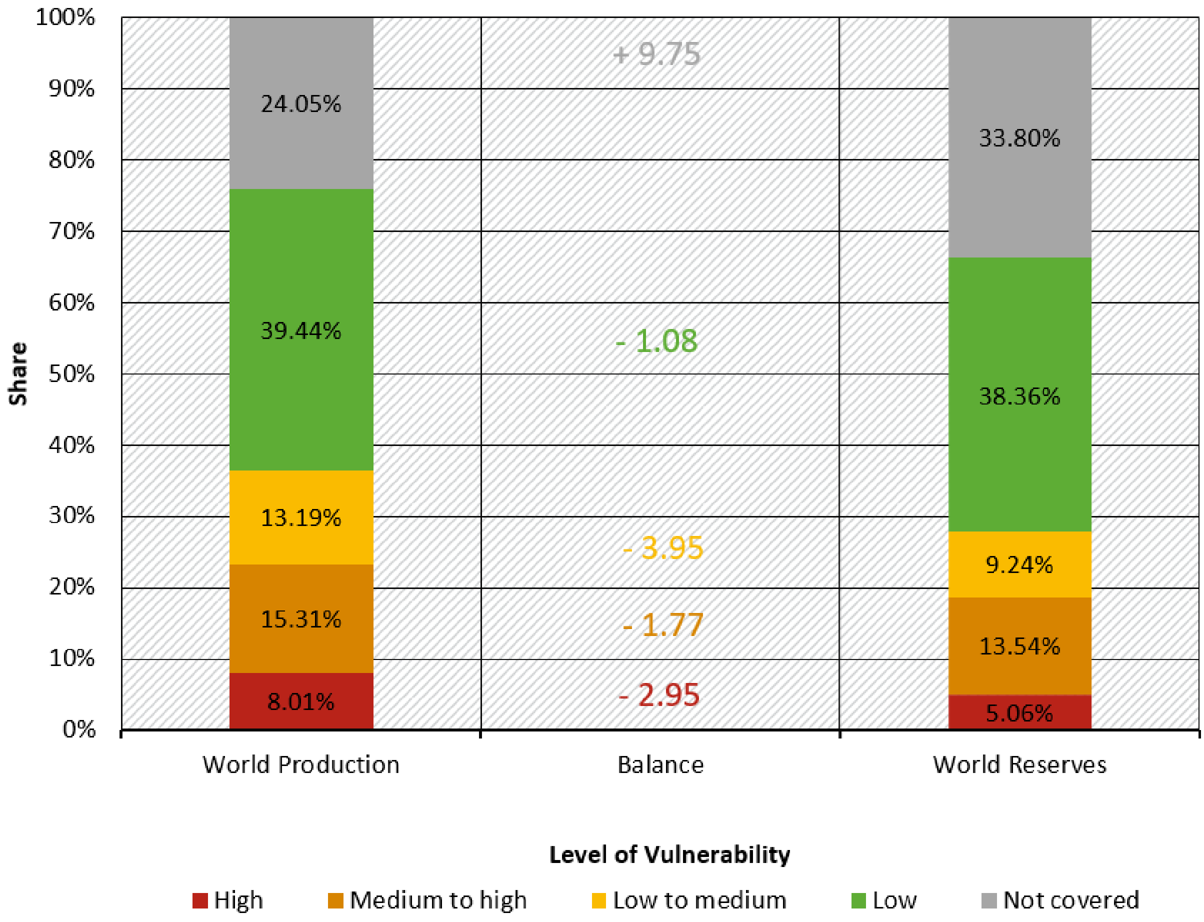
Table 11: Copper - Top Producing Countries and Reserves (2016) and corresponding ND-GAIN scores

Country	Share of world production	Share of world reserves	Overall vulnerability	Components of overall vulnerability		
				Exposure	Sensitivity	Adaptive Capacity
Chile	27.61% (Rank 1)	21.52% (Rank 1)	0.343	0.384	0.266	0.379
Peru	11.69% (Rank 2)	10.25% (Rank 3)	0.426	0.457	0.292	0.531
China	9.45% (Rank 3)	3.42% (Rank 6)	0.389	0.448	0.324	0.394
USA	7.11% (Rank 4)	5.70% (Rank 5)	0.339	0.481	0.271	0.265
Australia	4.72% (Rank 5)	11.14% (Rank 2)	0.294	0.480	0.119	0.273
DRC	4.21% (Rank 6)	2.53% (Rank 8)	0.589	0.494	0.447	0.817
Zambia	3.80% (Rank 7)	2.53% (Rank 8)	0.542	0.549	0.486	0.578
Mexico	3.74% (Rank 8)	5.82% (Rank 4)	0.382	0.487	0.253	0.407
Indonesia	3.62% (Rank 9)	3.29% (Rank 7)	0.445	0.518	0.287	0.531
Total	75.95%	66.20%				

Source: Own figure, results based on USGS (2018), ND-GAIN (2018).

The relatively widespread distribution of copper production and reserves is one possible explanation for the fact that no major differences are evident when comparing the vulnerability of current production countries to future ones – in other words, due to the large number of current and future producers from different regions, the levels of vulnerability remain on balance largely equal for current and future production (Figure 4).

Figure 4: Copper Production and Reserves – Vulnerability



Source: Own figure, results based on USGS (2018), ND-GAIN (2018).

3.3.4 Iron Ore

Table 12: Main characteristics of iron ore production and reserves

Characteristics	Production	Reserves
Coverage of the climate change vulnerability assessment	5 countries (covering 82.49% of world production)	5 countries (covering 75.19% of world reserves)
Relative vulnerability in comparison to all other materials covered in the report[17]	5th most vulnerable (of 9 raw materials covered)	6th most vulnerable (of 9 raw materials covered)

Source: Results based on USGS (2018), ND-GAIN (2018).

The production and reserves of iron ore are mainly located in five countries: Australia, Brazil, China, India and Russia (Table 12). Both the current and the expected future production of iron

[17] See Figures 11 and 12 below.

ore are largely concentrated in countries with low or low-to-medium vulnerability to climate change: Australia and Russia have low vulnerability, Brazil and China low-to-medium and India medium vulnerability (Table 13). It is remarkable that no iron ore-producing country is highly vulnerable to climate change.

While Australia and Russia have the strongest adaptive capacity of all iron ore producers, India has the weakest. Brazil and China have strong-to-medium adaptive capacity. However, all five countries are medium-to-highly exposed to climate change.

Table 13: Iron Ore - Top Producing Countries and Reserves (2016) and corresponding ND-GAIN scores

Country	Share of world production	Share of world reserves	Overall vulnerability	Components of overall vulnerability		
				Exposure	Sensitivity	Adaptive Capacity
Australia	36.62% (Rank 1)	28.92% (Rank 1)	0.294	0.480	0.119	0.273
Brazil	18.97% (Rank 2)	14.46% (Rank 3)	0.381	0.501	0.256	0.385
China	14.90% (Rank 3)	8.67% (Rank 4)	0.389	0.448	0.324	0.394
India	7.86% (Rank 4)	6.27% (Rank 5)	0.497	0.572	0.383	0.536
Russia	4.14% (Rank 5)	16.87% (Rank 2)	0.335	0.440	0.203	0.360
Total	82.49%	75.19%				

Source: Own figure, results based on USGS (2018), ND-GAIN (2018).

Decisive shifts from current production sites to more vulnerable production sites are not expected (Figure 5). However, the share of reserves in countries with low vulnerability increases slightly in the future, whereas the share of reserves in countries with low-to-medium and low vulnerability decreases because the second-largest reserves are located in Russia, which has a low vulnerability. The production of iron ore could therefore become less vulnerable in the future, decreasing the risk of negative environmental impacts and supply disruptions.

Figure 5: Iron Ore Production and Reserves – Vulnerability

Source: Own figure, results based on USGS (2018), ND-GAIN (2018).

3.3.5 Lithium

Table 14: Main characteristics of lithium production and reserves

Characteristics	Production	Reserves
Coverage of the climate change vulnerability assessment	4 countries (covering 95.79% of world production)	4 countries (covering 96.25% of world reserves)
Relative vulnerability in comparison to all other materials covered in the report[18]	Least vulnerable (of 9 raw materials covered)	Least vulnerable (of 9 raw materials covered)

Source: Results based on USGS (2018), ND-GAIN (2018).

Lithium production is highly concentrated – just four countries produce over 95% of the world's lithium (Table 14). The current production of lithium is dominated by Chile and Australia, which are responsible for over 70% of it. In the medium term, China could play an increasingly

[18] See Figures 11 and 12 below.

important role due to its large reserves. Lithium stands out in this report as the raw material with the most resilient production sites, both now and in terms of reserves. All major lithium producers have low or low-to-medium scores for vulnerability and strong or strong-to-medium adaptive capacities (Table 15). In addition, although most countries exhibit medium-to-high values for exposure to climate change, no country is critically exposed (i.e. has high exposure scores).

Table 15: Lithium - Top Producing Countries and Reserves (2016) and corresponding ND-GAIN scores

Country	Share of world production	Share of world reserves	Overall vulnerability	Components of overall vulnerability		
				Exposure	Sensitivity	Adaptive Capacity
Chile	37.63% (Rank1)	46.88% (Rank 1)	0.343	0.384	0.266	0.379
Australia	36.84% (Rank 2)	16.88% (Rank 3)	0.294	0.480	0.119	0.273
Argentina	15.26% (Rank 3)	12.50% (Rank 4)	0.368	0.470	0.253	0.380
China[19]	6.05% (Rank 4)	20.00% (Rank 2)	0.389	0.448	0.324	0.394
Total[20]	95.79%	96.25%				

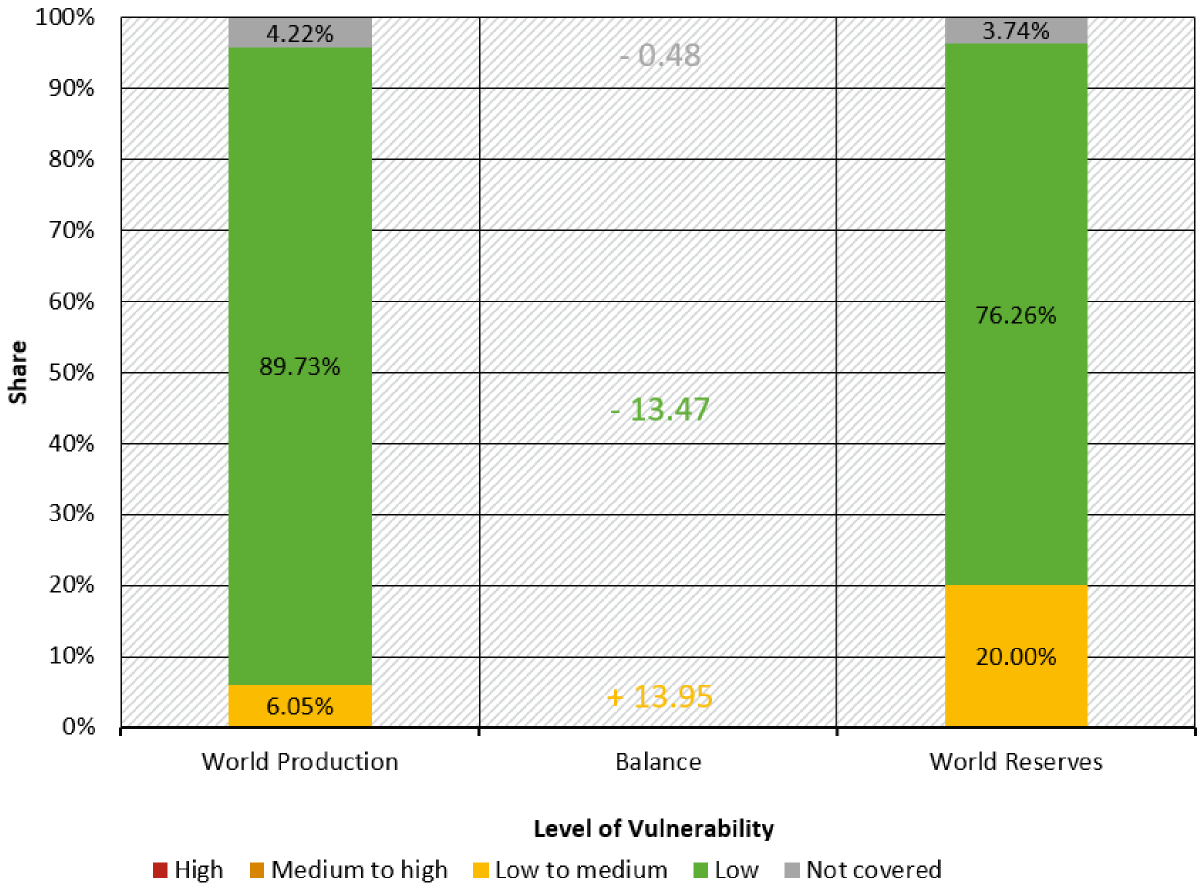
Source: Own figure, results based on USGS (2018), ND-GAIN (2018).

However, vulnerability is likely to increase slightly in the future. Due to China's large reserves and its higher vulnerability in comparison to the other countries, we expect future production to be more vulnerable than current production (Figure 6). As China – a country with low-to medium-vulnerability – has the larger reserves than current production, the share of low vulnerability decreases in the future.

[19] China was included because of its remarkable reserves (ranked second for reserves), although Chile, Australia and Argentina already account for more than 75% of world production.

[20] The total without China would be 89.74%.

Figure 6: Lithium Production and Reserves – Vulnerability



Source: Own figure, results based on USGS (2018), ND-GAIN (2018).

3.3.6 Nickel

Table 16: Main characteristics of nickel production and reserves

Characteristics	Production	Reserves
Coverage of the climate change vulnerability assessment	10 countries (covering 75.19% of world production)	9 countries (covering 82.17% of world reserves)
Relative vulnerability in comparison to all other materials covered in the report[21]	4th most vulnerable (of 9 raw materials covered)	4th most vulnerable (of 9 raw materials covered)

Source: Results based on USGS (2018), ND-GAIN (2018).

The production and reserves of nickel are among the most dispersed of all raw materials covered in this report, with no country currently dominating the market. Current production

[21] See Figures 11 and 12 below.

mainly takes place in countries with low vulnerability (31.7%) and medium-to-high vulnerability (31.2%). Exposure to climate change is quite high.

Table 17: Nickel - Top Producing Countries and Reserves (2016) and corresponding ND-GAIN scores

Country	Share of world production	Share of world reserves	Overall vulnerability	Components of overall vulnerability		
				Exposure	Sensitivity	Adaptive Capacity
Philippines	16.60% (Rank 1)	6.49% (Rank 5)	0.462	0.492	0.373	0.520
Canada	11.29% (Rank 2)	3.65% (Rank 9)	0.296	0.433	0.177	0.268
Russia	10.62% (Rank 3)	10.27% (Rank 3)	0.335	0.440	0.203	0.360
New Caledonia	9.90% (Rank 4)	No data	No data	No data	No data	No data
Australia	9.76% (Rank 5)	25.68% (Rank 1)	0.294	0.480	0.119	0.273
Indonesia	9.52% (Rank 6)	6.08% (Rank 6)	0.445	0.518	0.287	0.531
Brazil	7.66% (Rank 7)	16.22% (Rank 2)	0.381	0.501	0.256	0.385
China	4.69% (Rank 8)	3.92% (Rank 8)[22]	0.389	0.448	0.324	0.394
Guatemala	2.58% (Rank 9)	2.43% (Rank 10)	0.460	0.479	0.411	0.488
Cuba	2.47% (Rank 10)	7.43% (Rank 4)	0.426	0.497	0.346	0.424
Total[23]	75.19%	82.17%				

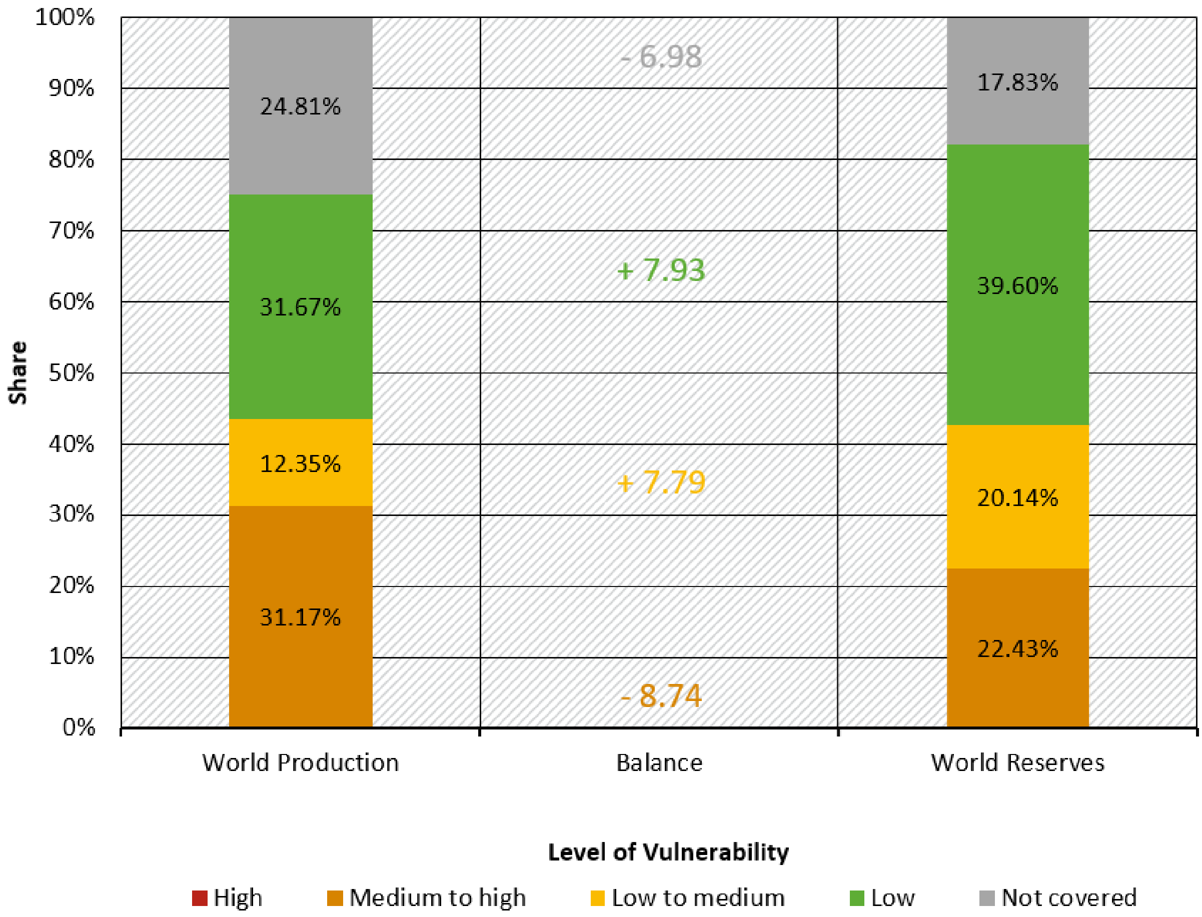
Source: Own figure, results based on USGS (2018), ND-GAIN (2018).

In the future, we expect the market share of countries with comparably low vulnerability to increase, mainly due to a drop in production in the Philippines (currently the leading world producer, but with rather small reserves) and an increase in production in Australia (currently roughly 10% of world production, but with highest amount of reserves worldwide) (Figure 7).

[22] Rank 7 is South Africa.

[23] Total does not include value for New Caledonia.

Figure 7: Nickel Production and Reserves – Vulnerability



Source: Own figure, results based on USGS (2018), ND-GAIN (2018).

3.3.7 PGMs

Table 18: Main characteristics of PGMs production and reserves

Characteristics	Production	Reserves
Coverage of the climate change vulnerability assessment	2 countries (covering 77.73% of world production)	2 countries (covering 96.96% of world reserves)
Relative vulnerability in comparison to all other materials covered in the report[24]	8th most vulnerable (of 9 raw materials covered)	8th most vulnerable (of 9 raw materials covered)

Source: Results based on USGS (2018), ND-GAIN (2018).

PGMs production and reserves are also highly concentrated. South Africa and Russia dominate the market, and South Africa is likely to further increase its market share in the future due to its extraordinary amount of reserves (91.3% of world reserves). As South Africa is more vulnerable

[24] See Figures 11 and 12 below.

to climate change and less capable of adapting to its consequences, climate change might have a larger impact on PGMs production in the future. At the same time, however, exposure to climate change for PGMs-producing countries is lower than for countries producing any other raw material covered in this report.

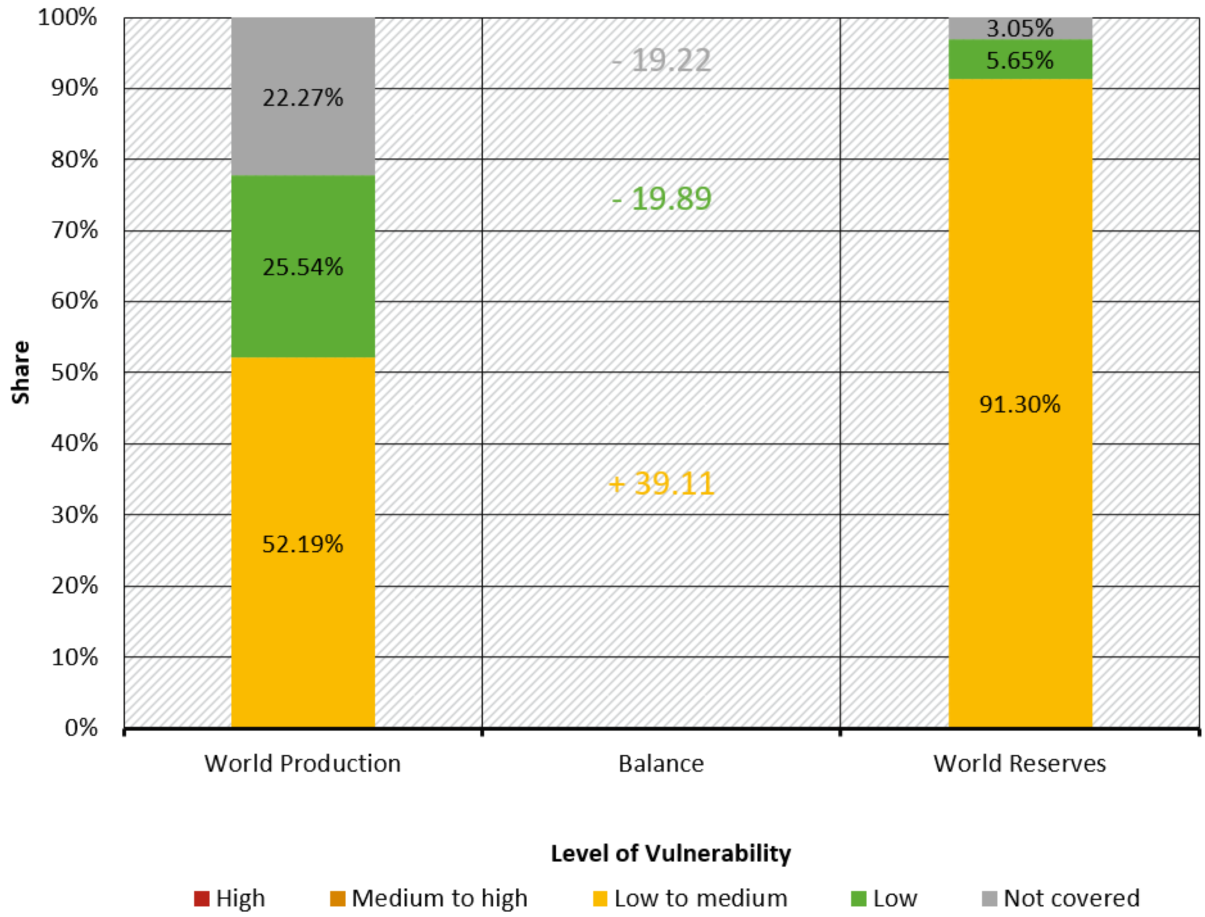
Table 19: PGMs - Top Producing Countries and Reserves (2016) and corresponding ND-GAIN scores

Country	Share of world production	Share of world reserves	Overall vulnerability	Components of overall vulnerability		
				Exposure	Sensitivity	Adaptive Capacity
South Africa	52.19% (Rank 1)	91.30% (Rank 1)	0.402	0.431	0.303	0.493
Russia	25.54% (Rank 2)	5.65% (Rank 2)	0.335	0.440	0.203	0.360
Total[25]	77,73%	96,96%				

Source: Own figure, results based on USGS (2018), ND-GAIN (2018).

[25] South Africa and Russia dominate the market. Next in current production are Canada (8.38%) and Zimbabwe (6.71%).

Figure 8: PGMs Production and Reserves – Vulnerability



Source: Own figure, results based on USGS (2018), ND-GAIN (2018).

3.3.8 Tin

Table 20: Main characteristics of tin production and reserves

Characteristics	Production	Reserves
Coverage of the climate change vulnerability assessment	7 countries (covering 92.28% of world production)	7 countries (covering 77.25% of world reserves)
Relative vulnerability in comparison to all other materials covered in the report[26]	Most vulnerable (of 9 raw materials covered)	3rd most vulnerable (of 9 raw materials covered)

Source: Results based on USGS (2018), ND-GAIN (2018).

Current tin production and reserves are rather dispersed (Table 20). Most production originates from (South) East Asia and South America. On average, tin-producing countries are the most vulnerable among all countries covered in this report and have comparably weak adaptive

[26] See Figures 11 and 12 below.

capacity. In addition, no other raw material has higher scores for exposure to climate change for both production and reserves (Table 21).

Table 21: Tin - Top Producing Countries and Reserves (2016) and corresponding ND-GAIN scores

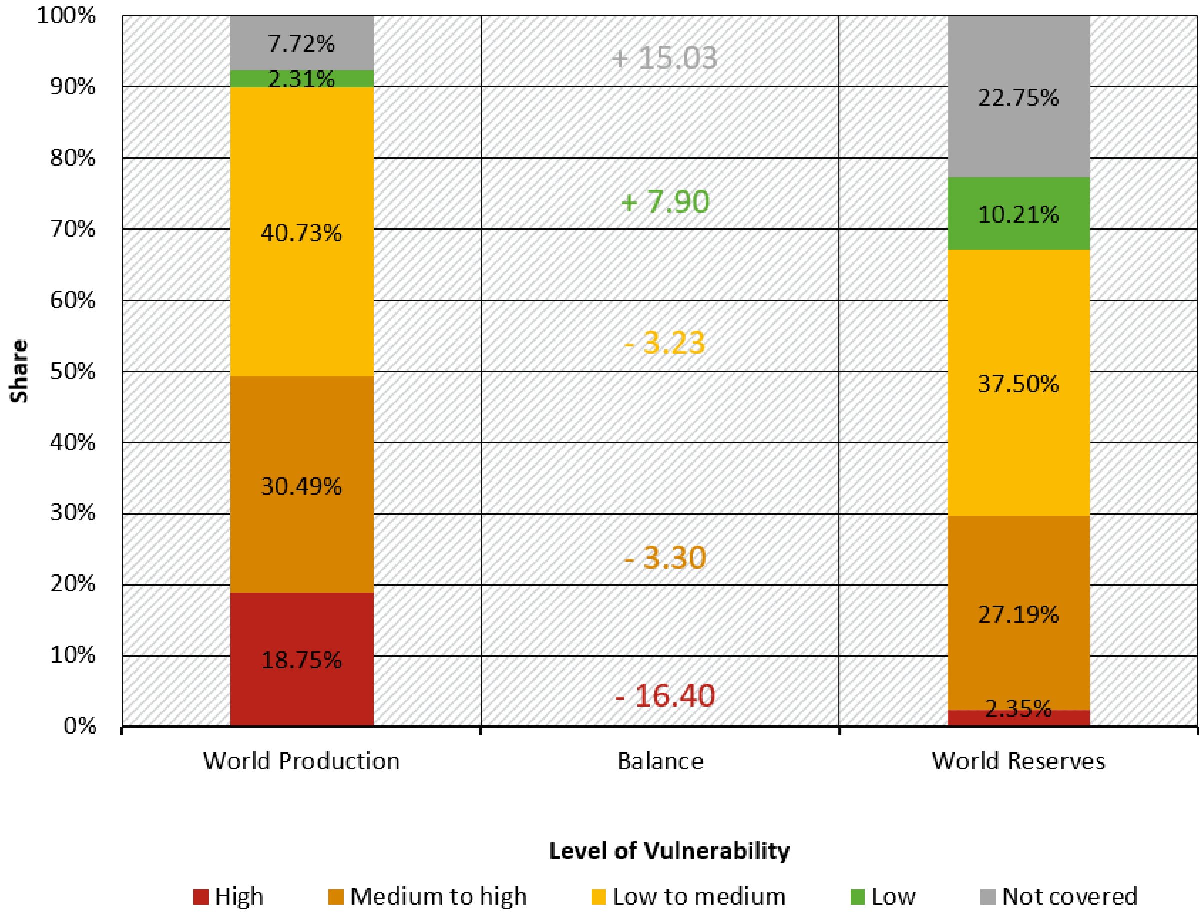
Country	Share of world production	Share of world reserves	Overall vulnerability	Components of overall vulnerability		
				Exposure	Sensitivity	Adaptive Capacity
China	31.94% (Rank 1)	22.92% (Rank 1)	0.389	0.448	0.324	0.394
Myanmar	18.75% (Rank 2)	2.35% (Rank 10)[27]	0.542	0.565	0.429	0.625
Indonesia	18.06% (Rank 3)	16.67% (Rank 2)	0.445	0.518	0.287	0.531
Brazil	8.79% (Rank 4)	14.58% (Rank 3)	0.381	0.501	0.256	0.385
Peru	6.53% (Rank 5)	2.19% (Rank 11)	0.426	0.457	0.292	0.531
Bolivia	5.90% (Rank 6)	8.33% (Rank 5)	0.460	0.448	0.354	0.596
Australia	2.31% (Rank 7)	10.21% (Rank 4)	0.294	0.480	0.119	0.273
Total	92.28%	77.25%				

Source: Own figure, results based on USGS (2018), ND-GAIN (2018).

Average vulnerability is likely to decrease in the future due to a drop in production in Myanmar and the increase in production in Australia (Figure 9).

[27] Rank 6-9 are: Russia (7.29%), Malaysia (5.21%), Thailand (3.54%), the DRC (3.13%). The current list does thus not capture the full shift between current and (potentially) future production.

Figure 9: Tin Production and Reserves – Vulnerability



Source: Own figure, results based on USGS (2018), ND-GAIN (2018).

3.3.9 Tungsten

Table 22: Main characteristics of tungsten production and reserves

Characteristics	Production	Reserves
Coverage of the climate change vulnerability assessment	3 countries (covering 92.63% of world production)	4 countries (covering 73.28% of world reserves)
Relative vulnerability in comparison to all other materials covered in the report[28]	6th most vulnerable (of 9 raw materials covered)	7th most vulnerable (of 9 raw materials covered)

Source: Results based on USGS (2018), ND-GAIN (2018).

China dominates current world production of tungsten (81.7% of current world production), and this will likely continue in the near future as China also has 56.3% of world reserves. The

[28] See Figures 11 and 12 below.

increasing concentration of production in China will also move production to less exposed areas because China has a relatively low vulnerability score.

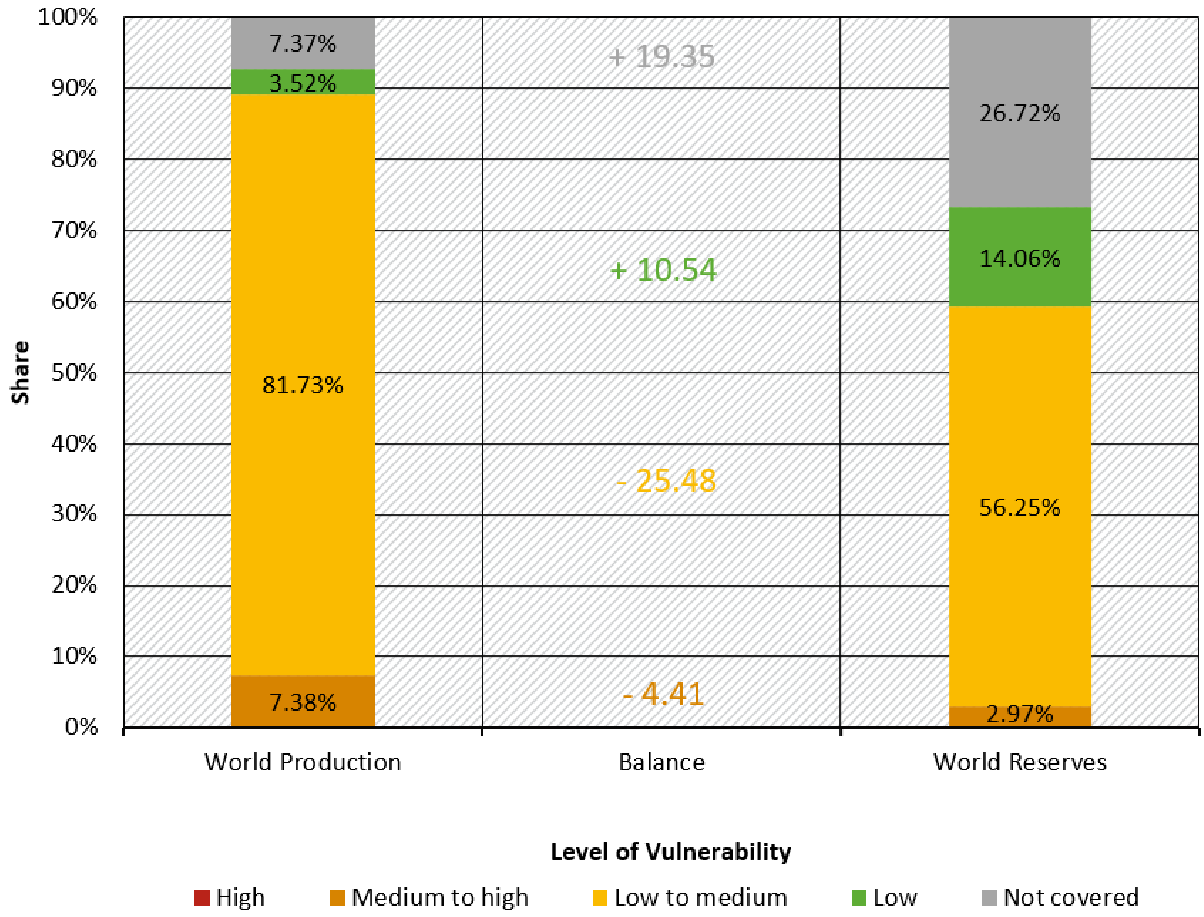
Table 23: Tungsten - Top Producing Countries and Reserves (2016) and corresponding ND-GAIN scores

Country	Share of world production	Share of world reserves	Overall vulnerability	Components of overall vulnerability		
				Exposure	Sensitivity	Adaptive Capacity
China	81.73% (Rank 1)	56.25% (Rank 1)	0.389	0.448	0.324	0.394
Vietnam	7.38% (Rank 2)	2.97% (Rank 4)	0.475	0.491	0.451	0.482
Russia	3.52% (Rank 3)	5.00% (Rank 3)	0.335	0.440	0.203	0.360
Canada	-	9.06% (Rank 2)	0.296	0.433	0.177	0.268
Total	92.63%	73.28%				

Source: Own figure, results based on USGS (2018), ND-GAIN (2018).

As China has rather good scores for vulnerability (i.e. low to medium vulnerability) and adaptive capacity (i.e. strong-to-medium adaptive capacity), the effects of climate change on tungsten production are expected to be small in comparison to those on other raw materials (Figure 10). The outlook might even be somewhat positive because of tungsten reserves in Canada and Russia, both countries with a low vulnerability to climate change.

Figure 10: Tungsten Production and Reserves – Vulnerability



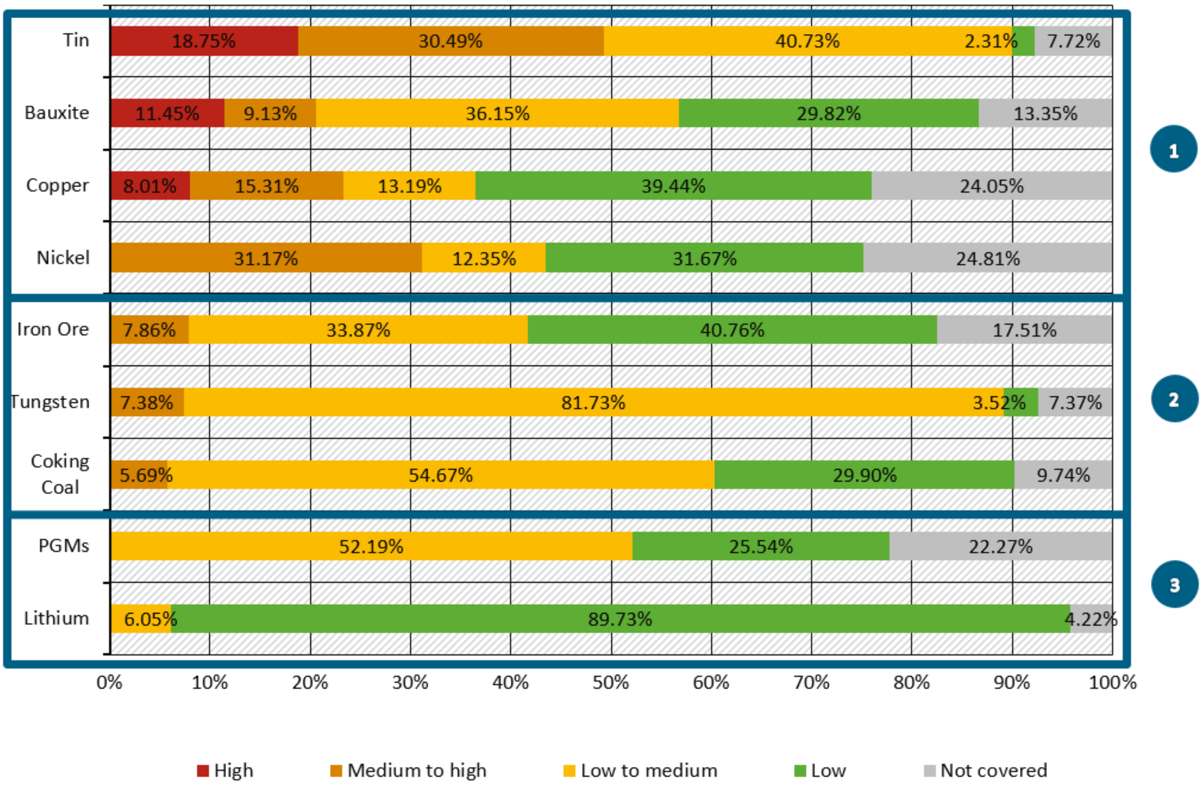
Source: Own figure, results based on USGS (2018), ND-GAIN (2018).

3.4 Climate change vulnerability ranking of all nine raw materials

To provide an overview of all nine raw materials assessed, we ranked the respective results according to the vulnerability of their producing countries (Figure 11). The raw materials can be divided into three groups according to the vulnerability of the countries they are produced in:

- Group 1: Raw materials produced in countries with high and high-to-medium vulnerability: tin, bauxite, copper and nickel.
- Group 2: Raw materials produced in countries with mostly medium-to-low vulnerability: iron ore, tungsten and coking coal.
- Group 3: Raw materials produced in countries with lower vulnerability: PGMs and lithium.

Figure 11: Comparison of the vulnerability of producing countries

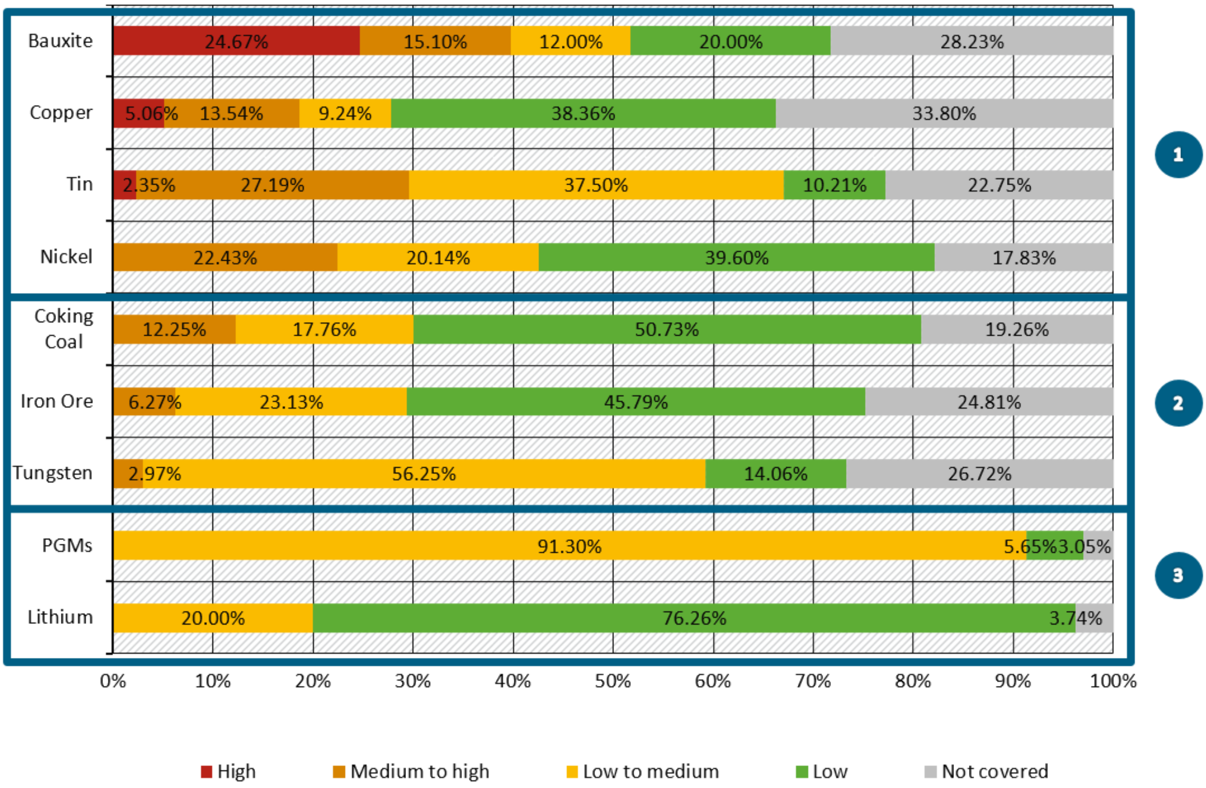


Source: Own figure, results based on USGS (2018), ND-GAIN (2018).

As described above, the forecast is based on the assumption that production will converge with the distribution of today's reserves. Figure 12 shows the distribution of reserves (classified by climate change vulnerability). The picture slightly changes for reserves: the raw materials stay in the same vulnerability group, yet the ranking of raw materials per group changes:

- Group 1: A large share of bauxite reserves is located in vulnerable countries. On the other hand, bauxite production currently takes place in less vulnerable countries. On balance, future bauxite production sites might be more vulnerable than current production sites. Copper, tin and nickel reserve countries are slightly less vulnerable than the respective producing countries. Therefore, future production might be less vulnerable than current production.
- Group 2: Coking coal reserve countries are slightly more vulnerable than coking coal producing countries. Thus, coking coal mining in the future might be more vulnerable than current production. In the future, the vulnerability for countries with iron ore reserves remains almost the same, while the vulnerability of future tungsten production is lower than current tungsten production.
- Group 3: Countries with PGMs and lithium reserves continue to have a low vulnerability in the future. However, the share of reserves with low-to-medium vulnerability is higher than the share of production in countries with low-to-medium vulnerability.

Figure 12: Comparison of the vulnerability of reserves

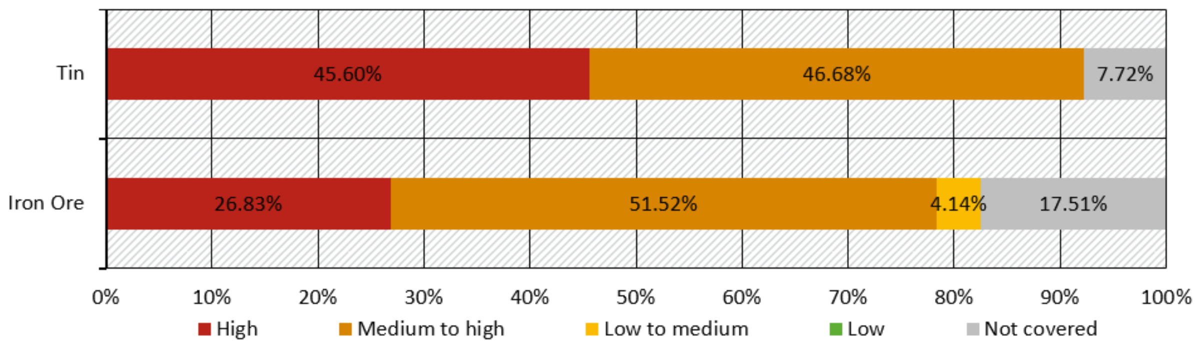


Source: Own figure, results based on USGS (2018), ND-GAIN (2018).

3.5 Crucial factors in determining vulnerability: Exposure and adaptive capacity

The results of the climate change vulnerability assessment of the different raw materials underline the importance of a country's exposure and adaptive capacity. To illustrate that, we compare these two variables and the vulnerability of tin- and iron ore- producing countries. Both tin- and iron ore-producing countries have a high exposure score (Figure 13). Furthermore, Annex C includes a complete overview of exposure and adaptive capacity for all raw materials.

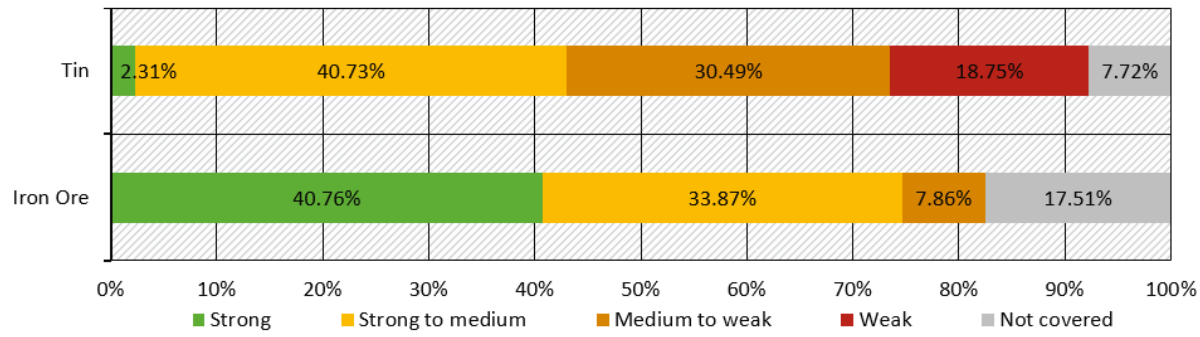
Figure 13: Tin and Iron Ore Production - Exposure



Source: Own figure, results based on USGS (2018), ND-GAIN (2018).

However, tin- and iron ore-producing countries have very different levels of adaptive capacity. While tin-producing countries have a weak and medium-to-weak adaptive capacity, iron ore-producing countries have a strong and strong-to-medium adaptive capacity (Figure 14).

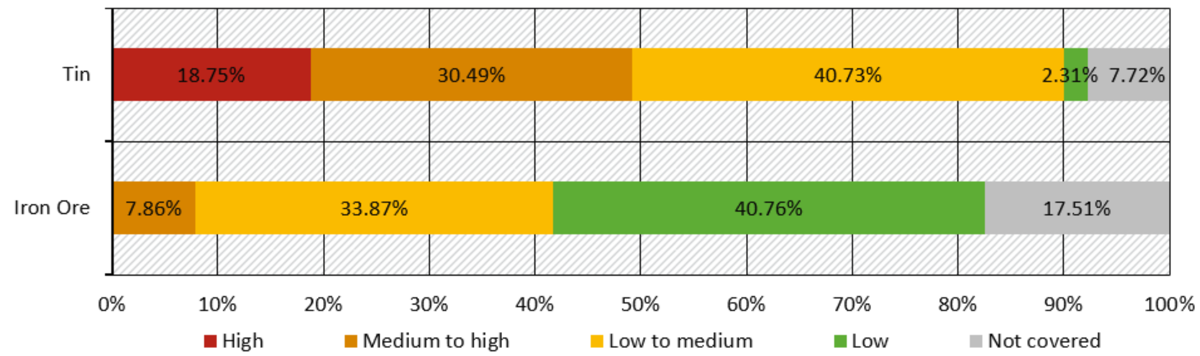
Figure 14: Tin and Iron Ore Production - Adaptive Capacity



Source: Own figure, results based on USGS (2018), ND-GAIN (2018).

In terms of vulnerability, this means that tin-producing countries have a quite high vulnerability while the vulnerability of iron ore-producing countries is mostly low or low-to-medium (Figure 15).

Figure 15: Tin and Iron Ore Production - Vulnerability



Source: Own figure, results based on USGS (2018), ND-GAIN (2018).

This underlines the importance of improving adaptation capacities: vulnerability is considerably lower when adaptive capacity is strong. The adaptive capacity of countries can be improved to make them more resilient.

However, exposure is still a very relevant factor. Experience shows that countries with a high adaptive capacity can also be negatively impacted by climate change impacts (e.g. the severe floods in Australia in 2010-2011 and 2017 that affected the global coal market or water restrictions due to droughts in Chile that affected copper production).

4 Conclusions

The mining sector urgently needs to develop strategies for climate change adaptation in order to manage future environmental risks to mining and increase resilience of mining operations. The climate change impacts identified in the case studies and summarised in this report represent a range of potential effects on mining and processing sites. Based on our analysis, we have reached the following conclusions.

Mining operations need to prepare for extreme weather events and climate variability

Extreme weather events, in particular flooding, stand out as the main risk, both in terms of environmental impacts and disruption of supply across different raw materials, mining sites and climatic zones. The failures of large tailings dams are particularly dangerous as these not only result in extensive environmental damage but also often destroy livelihoods, damage infrastructure and even cause fatalities.

Mining operations have always faced extreme weather, but climate change increases the frequency and intensity of extreme events. So when assessing climate change impacts and developing and implementing adaptation plans, the mining sector needs to focus on extreme weather events, especially with regard to tailings dam safety. In this context, one particular challenge is to identify the impacts of combined or sequential extreme events.

However, the impacts of slow-onset, gradual changes also need to be taken into account. These are often less evident than the impacts of sudden, extreme events, but they are nevertheless important. Further in-depth research is required to fill these knowledge gaps.

Biodiversity and communities are affected by multiple stressors and require comprehensive understanding

The impacts of mining operations interact with other pressures (e.g. water stress) to put additional stress on biodiversity and local communities. Climate change can act as a 'risk multiplier', which means that it can exacerbate various risks already prevalent in the mining region (e.g. water stress). These interactions have to be assessed very carefully. In addition, in this heightened risk context, it will become more important to establish and maintain good relationships with local communities.

Climate change challenges rehabilitation

Rehabilitation is key for mitigating negative environmental impacts of former mining sites and returning the land disturbed by mining to sustainable conditions. However, mine rehabilitation is often challenging. Climatic changes, such as changing temperature and precipitation regimes and extreme weather events, will make this task even more difficult, especially in view of the long timeframe of rehabilitation. Thorough long-term rehabilitation planning and implementation – that starts successively during mining operation, takes into account climate change projections and adjusts to future climate change impacts – is therefore crucial.

Only a few, ambiguous positive impacts

In our case studies, we could identify only a small number of positive impacts linked to climate change, and potential negative impacts clearly outweigh positive impacts. Based on these findings, mining production will probably not benefit considerably from climate change. Furthermore, all positive impacts have to be closely assessed, as the aforementioned example on opening transport routes in Canada illustrates (see chapter 4.5).

Additional climate change impacts might occur at mining and production sites

The findings of this report are mainly based on climate changes impacts identified in the five case studies. Thus, they cannot give a complete picture of all potential climate change impacts on mining. Additional or different climate change impacts might occur. Comprehensive and individual vulnerability assessments are therefore necessary to assess risks specific to a mining or production site.

Climate change vulnerability assessment allows initial assumptions

The climate change vulnerability assessment of the nine raw materials in this report allows us to draw conclusions about the vulnerability of the primary production of certain raw materials. Tin, bauxite, copper and nickel production is mostly located in vulnerable countries, and these raw materials are therefore among the most vulnerable. In comparison, iron ore-, tungsten- and coking coal-producing countries are less vulnerable. PGMs and lithium make up the least vulnerable group of raw materials in terms of production countries.

Underlying components of vulnerability are important

This assessment further indicates which production countries have higher or lower vulnerability. Raw material supply from countries with a low vulnerability is more secure, but we cannot rule out that climate change will also have significant negative impacts in these countries. Experience shows that even if the adaptive capacity of a country is high, supply disruptions can occur – especially if exposure is high. According to our assessment, no country with raw material production or reserves covered in this report has a low exposure. This underlines the fact that that all production sites, regardless of their adaptive capacity, can be potentially affected by climate change impacts and that adapting to negative climate change impacts is crucial across all countries. It also shows that avoiding sourcing raw materials from highly vulnerable countries is not advisable. Instead, the strengthening of weak adaptive capacities in producing countries should be supported. In addition, we recommend diversifying sources of supply and increasing the use of secondary material where possible.

Limitations of the vulnerability assessment and further considerations

When referring to the results of the vulnerability assessment, it needs to be kept in mind that vulnerability indexes do not capture all dimensions of vulnerability to climate change. Thus, the assessment can only serve as a starting point to identify potentially vulnerable countries whose raw material production can be examined closer in a next step.

Future research projects could focus on additional aspects. Instead of assessing the vulnerability of production and reserves, future projects could base the assessment on data for individual mining sites or mineral deposits. However, data on vulnerability is limited at this scale. However, the exposure of mining sites or mineral deposits could be assessed based on spatial data of downscaled climate change projection. This data could be analysed using GIS approaches. In addition, the scenarios for future shifts of raw material production could be refined. It is not only the location of reserves but also other factors (e.g. price developments, new technologies and geopolitics) that determine where raw materials are or will be mined. These additional factors could be fed into a complex model to project shifts in the production of raw materials.

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A Appendix A

Table 24: Description of environmental categories and potential climate change induced impacts

Environmental categories	Description of category	Climate change impact assessment on environmental categories relating to mining /processing. Climate impact on:
Land use	This category covers the area of land used for mining and processing activities (i.e. land footprint). It entails impacts on land consumption for mining and processing. Land use has also impacts on biodiversity and rehabilitation (see below).	- In general, climate impacts do not change land consumption (the size of the mining pit does not change due to climatic changes). - Exception: Erosion/landslide and flooding can contribute to the land degradation in Indonesia. This is due to bucket-line dredging of placer tin deposits, which removes the top soil of large areas.
Water use[29]	This category covers the use of water for mining and processing. Important aspects therefore are the amount of water used and the general water availability/competition in the mining area and the water sources. Water use can also have impacts on Biodiversity.	- Drought: less water availability (competition in water use, less water available for dust suppression)
Energy use[30]	This category covers the use of energy for mining and processing. It is important to consider the amount of energy used for mining and processing and also the energy sources (fossil vs. renewable, grid or on-site)	- No direct climate impacts detected - Indirect impact if more energy is required e.g. for desalination
Waste	This category covers the waste produced during mining and processing. It is important to include the amount/ type of waste, the storage and (potential) emissions from waste to water, soil or air. Important characteristics are e.g., AMD, heavy metals or the use of toxic auxiliary substances. Waste from mining/processing can also have impacts on Biodiversity, Rehabilitation and Health.	- Drought: Concentration of pollutants in tailings - Flooding: Spill of tailings, flushing out of pollutants, potential tailings dam breach

[29] Note: Water quality issues after use and waste water is covered in the category 'waste' through occurred emissions from waste or the potential of emissions to water from waste storage.

[30] Note: GHG emissions are covered in the category 'air emissions'.

Environmental categories	Description of category	Climate change impact assessment on environmental categories relating to mining /processing. Climate impact on:
Air emissions[31]	This category covers air emissions (dust and particulate matter, GHG emissions, other gases) that arise during mining and processing: What is the amount, type, toxicity of air emissions? The provision of technical safety measures (e.g. filters) can reduce the environmental impact of air emissions. Air emissions can also have impacts on Biodiversity and Health.	- Wind: Dispersion of dust from mining - In general: The dispersion of air emissions is affected by weather conditions, such as wind speed and direction, air temperature and precipitation. - Temperature inversion and light wind can lead to elevated levels of air emissions. It is difficult to evaluate whether climatic changes will lead to an increased frequency of such unfavourable weather conditions.
Rehabilitation	Land rehabilitation is "the return of disturbed land to a stable and productive condition" (ICMM, n.d.). Important aspects are the difficulty for rehabilitation of the site (e.g. climate, toxics), existing plans for rehabilitation in place and the organisation of long-term waste management.	- Climate change can make rehabilitation more difficult and less successful. - Change in temperature and precipitation regime and other extreme events (e.g. droughts, heat waves, fires, flooding, erosion/landslides) have impacts on plant development (important for revegetation). - Impacts on other rehabilitation measures still need to be assessed in detail
Biodiversity	This category covers impacts of mining and processing on biodiversity in the area of operation. These impacts can degrade or damage biodiversity features or ecosystems, including the destruction of soil, water ways, vegetation and habitat of animals.	- Climatic changes put pressure on biodiversity, degraded or damaged by mining and processing operations.
Health	This category covers adverse health impacts linked to mining and processing. These include health impacts arising from the working environment (e.g. harsh climate, remoteness, altitude), the provision of occupational safety measures or other health impacts from operations (e.g. handling of toxic and/or radioactive substances, noise or inhalation of dust/particulate matter)	- Climate change can render the working environment harsher (e.g. heat waves, dangers from wildfire, flooding, cyclones, more malaria-transmitting mosquitoes, cut-off the transport infrastructure). - Climate change has more impacts when few or no occupational safety measures are in place (e.g. ASM mining in Indonesia is exposed to more hazards in times of flooding). Other impacts are lack of water for dust suppression or flushing out of toxic or radioactive substances.

[31] Note: Soil and water emissions are covered in the category waste through occurred emissions from waste or the potential of emissions to water/soil from waste storage.

General remarks on climate stimuli and direct climate impacts:

The UBA Guidelines for climate impact and vulnerability assessment define the term 'climate stimuli' the following way: "Climate stimuli are described by climate parameters that are relevant for a climate impact such as temperature, precipitation, wind, etc." (UBA, 2017: 10). A direct climate impact is caused by a climate stimulus (e.g. river floodings or flash floodings as a result of heavy rain) or several climate stimuli.

The actual occurrence of each of direct climate impacts (e.g. flooding, erosion, landslides, heat waves, wildfires) depends on the local conditions (e.g. vegetation cover, slope, soil conditions, coastal or continental location) and on the complex interplay of various factors.[32]

Table 25: Description of climate stimuli and direct climate impacts (hazard types)

Climate stimuli and direct climate impact	Description of category	Potential impacts on
Increase of mean temperature (slow-onset, gradual change)	Mean temperature can be defined as "[t]he average daily maximum air temperature, for each month and as an annual statistic, calculated overall years of record" (BoM, 2007a). This category covers projections, which show an increase in mean temperature. Global climate change projections: "Relative to 1850–1900, global surface temperature change for the end of the 21st century (2081–2100) is projected to likely exceed 1.5°C for RCP4.5, RCP6.0 and RCP8.5 (high confidence). Warming is likely to exceed 2°C for RCP6.0 and RCP8.5 (high confidence), more likely than not to exceed 2°C for RCP4.5 (medium confidence), but unlikely to exceed 2°C for RCP2.6 (medium confidence)" (IPCC, 2014: 60).	**Environmental impacts** - Increased risk of mined land rehabilitation failure (e.g. plant development potentially reacts sensitively to elevated temperatures) - Biodiversity stressed **Disruption of mining operations** - Workforce capacity reduced (e.g. increased transmission of malaria and dengue)
Increase of mean precipitation (slow-onset change, gradual change)	"Precipitation is most often rain (hence the common term), but also includes other forms such as snow". Mean precipitation is the "arithmetically averaged total amount of precipitation recorded during a calendar month or year. Both mean and median rainfall are included in these statistics, although from the meteorological point of view the median is usually the preferred measure of 'average' or	**Environmental impacts** - No expected direct impacts on rehabilitation success and biodiversity **Disruption of mining operations**

[32] The IPCC states that "[i]mpacts on the physical environment [i.e. direct climate impacts] […] are often the result of compound events. For instance, floods will more likely occur over saturated soils […], which means that both soil moisture status and precipitation intensity play a role. The wet soil may itself be the result of a number of above-average but not necessarily extreme precipitation events, or of enhanced snow melt associated with temperature anomalies in a given season. Similarly, droughts are the result of pre-existing soil moisture deficits and of the accumulation of precipitation deficits and/or evapotranspiration excesses […], not all (or none) of which are necessarily extreme for a particular drought event when considered in isolation" (IPCC, 2012: 118).

Climate stimuli and direct climate impact	Description of category	Potential impacts on
	'typical' rainfall.” (BoM, 2007a). This category covers projections that show an increase in mean precipitation. Changes in precipitation in a warming world will not be uniform. For example, the high latitudes and the equatorial Pacific are likely to experience an increase in annual mean precipitation by the end of this century meanwhile in many mid-latitude and subtropical dry regions, mean precipitation will likely decrease under the RCP8.5 scenario (IPCC, 2014: 60).	- Workforce capacity reduced (e.g. increased transmission of malaria and dengue)
Decrease of mean precipitation (slow-onset change, gradual change)	See above ‘increase of mean precipitation’.	**Environmental impacts** - Risks and failures in mined land rehabilitation - Biodiversity stressed **Disruption of mining operations** - No potential supply disruptions due to this climate stimuli/direct climate impact
Occurrence of heat waves (sudden-onset, extreme event)	A heat wave is defined as a “period of marked unusual hot weather […] over a region persisting at least three consecutive days during the warm period of the year based on local (station-based) climatological conditions” (WMO, 2018). Some results indicates that the percentage of global area affected by heat waves has increased. Model predictions reveal an increase in the occurrence of extreme heatwaves in the coming years (Russo et al., 2014).	**Environmental impacts** - Reduced resilience of rehabilitated mined land (e.g. suppression of growth and/or loss of vegetation due to heat stress) - Biodiversity stress **Disruption of mining operations** - Extreme heat damage to road and rail infrastructure - Workforce capacity reduced due to heat stress
Occurrence of droughts (slow-onset, extreme event)	Drought is defined as a “period of abnormally dry weather long enough to cause serious hydrologic imbalances” (IPCC, 2014), resulting “in a water shortage for some activity, group or environmental sectors” (ActionAid, 2016). Climate change projections show “that droughts will intensify in the 21st century in	**Environment impacts** - Reduced resilience of rehabilitated mined land (e.g. plant development which reacts sensitively to water stress) - Biodiversity stress - Increased sensitivity to pollution loading in surface watersheds **Disruption of mining operations** - Reduced production at mine site due to water shortages

Climate stimuli and direct climate impact	Description of category	Potential impacts on
	some seasons and areas [33], due to reduced precipitation and/or increased evapotranspiration" (IPCC, 2012).	
Occurrence of wildfires (sudden-onset, extreme event)	A wildfire can be defined as "uncontrolled and non-prescribed combustion or burning of plants in a natural setting such as a forest, grassland, brush land or tundra, which consumes the natural fuels and spreads based on environmental conditions (e.g., wind, topography)" (EM-DAT, 2009). Although, the IPCC 2012 does not make projections for wildfires, an increase in droughts, in combination with heat and a decreased precipitation, can lead to more wildfires.	**Environmental impacts** - Smoke from fire combined with dust and air emissions from mining/processing can lead to increased levels of air pollution - Reduced resilience of rehabilitated land (loss of vegetation due to fire, degraded soil) - Biodiversity stress **Disruption of mining operations** - Damage to transportation infrastructure - Workforce capacity reduced due to evacuation of workforce
Occurrence of heavy rain events[34] (sudden-onset, extreme event)	Heavy rain can be defined as a "marked precipitation event occurring during a period of time of one to several days with daily total precipitation exceeding a certain threshold defined for a given location" (WMO, 2018). Climate change projections show that it "is likely that the frequency of heavy precipitation or the proportion of total rainfall from heavy rainfalls will increase in the 21st century over many areas of the globe, particularly in the high latitudes and tropical regions and in winter in the northern mid-latitudes. Heavy rainfalls associated with tropical cyclones are likely to increase with continued warming induced by enhanced greenhouse gas concentrations" (IPCC, 2012).	**Environmental impacts:** see 'occurrence of flooding' **Supply:** see 'occurrence of flooding'

[33] "This applies to regions including southern Europe and the Mediterranean region, central Europe, central North America, Central America and Mexico, northeast Brazil, and southern Africa. Elsewhere there is overall low confidence because of inconsistent projections of drought changes (dependent both on model and dryness index). Definitional issues, lack of observational data, and the inability of models to include all the factors that influence droughts preclude stronger confidence than medium in drought projections" (IPCC, 2012).

[34] Note: we merged the categories heavy rain and flooding, as the most important direct climate impact of heavy rain is flooding.

Climate stimuli and direct climate impact	Description of category	Potential impacts on
Occurrence of flooding events[35] (sudden-onset, extreme event)	Flooding is the "overflowing of the normal confines of a stream or other body of water, or the accumulation of water over areas not normally submerged" (IPCC, 2014). "Flooding occurs commonly from heavy rainfall when natural watercourses lack the capacity to convey excess water. It can also result from a storm surge associated with a tropical cyclone, a tsunami or a high tide. Climatological parameters that are likely to be affected by climate change are precipitation, windstorms, storm surges and sea-level rise" (UNISDR, 2017). There is "[l]ow confidence in [climate] projections of changes in floods because of limited evidence and because the causes of regional changes are complex. However, [there is] medium confidence that projected increases in heavy precipitation will contribute to rain-generated local flooding in some catchments or regions" (IPCC, 2012).	**Environmental impacts** - Land degradation and erosion - Water contamination - Unscheduled release of contaminated effluents - Reduced resilience of rehabilitated mined land (e.g. damaged plants, wash outs) - Biodiversity stress **Disruption of mining operations** - Lost production due to flooding - Damage to transportation infrastructure - Workforce capacity reduced due to evacuation of workforce
Occurrence of erosion/landslide (slow-onset, gradual event / sudden-onset, extreme event)	Erosion can be defined as the removal of surface material by flowing agents such as air, water or ice (USGS, n.d.). It can occur as soil or coastal erosion. Landslides[36] can be defined as a "variety of processes that result in the downward and outward movement of slope-forming materials, including rock, soil, artificial fill, or a combination of these. The materials may move by falling, toppling, sliding, spreading, or flowing […] (UNISDR, 2017). As both phenomena have similar impacts, they are considered together in one category. Climate change projections show that "[t]here is high confidence that changes in heat waves, glacial retreat, and/or permafrost degradation will affect high-mountain phenomena such as slope instabilities, mass movements, and glacial lake outburst floods. There is also high confidence that changes in heavy precipitation will affect landslides in some regions" (IPCC, 2012).	**Environmental impacts** - Reduced resilience of rehabilitated mined land (not only revegetation but also landscape) - Biodiversity stress **Disruption of mining operations** - Lost production - Damage to transportation infrastructure - Workforce capacity reduced due to evacuation of workforce

[35] Note: Flooding can be caused by heavy rain, storm surges, sea level rise (we make no distinction between freshwater and saltwater flooding).

[36] 'Mass movement' is the general term for all kinds of surface movements caused by gravity. Although the term 'landslide' refers restrictively speaking only to specific forms of mass movements, it is commonly used to refer to various kinds of mass movements (USGS, 2004).

Climate stimuli and direct climate impact	Description of category	Potential impacts on
Occurrence of cyclones/typhoons/hurricanes[37] (sudden-onset, extreme event)	A cyclones/typhoons/hurricanes (different names depending on where they appear) can be defined as a “rotating, organized system of clouds and thunderstorms that originates over tropical or subtropical waters and has closed, low-level circulation” (NOAA, n.d.). “Cyclones bring with them high wind speeds, rainfall and bad weather. The onset of a cyclone is extensive and damage associated with a high intensity cyclone is usually severe, especially to fragile infrastructure […]. This is followed by heavy rains which can trigger floods spread over large areas due to tidal waves” (ActionAid, 2016). Climate change projections show that it is “[l]ikely that the global frequency of tropical cyclones will either decrease or remain essentially unchanged. Likely increase in average tropical cyclone maximum wind speed, although increases may not occur in all ocean basins. Heavy rainfalls associated with tropical cyclones are likely to increase. Projected sea level rise is expected to further compound tropical cyclone surge impacts” (IPCC, 2012).	**Environmental impacts:** see ‘occurrence of flooding’ and ‘occurrence of wind’ **Supply:** see ‘occurrence of flooding’ and ‘occurrence of wind’
Occurrence of heavy waves/storm surge (sudden-onset, extreme event)	Extreme form of a heavy wave is a storm surge, which can be defined as the “temporary increase, at a particular locality, in the height of the sea due to extreme meteorological conditions (low atmospheric pressure and/or strong winds). The storm surge is defined as being the excess above the level expected from the tidal variation alone at that time and place” (IPCC, 2014).	**Environmental impacts:** see ‘occurrence of flooding’ **Supply:** see ‘occurrence of flooding’
Occurrence of heavy wind (sudden-onset, extreme event)	Climate change projections show that there “is generally low confidence in projections of changes in extreme winds because of the relatively few studies of projected extreme winds, and shortcomings in the simulation of these events. An exception is mean tropical cyclone maximum wind speed, which is likely to increase, although increases may not occur in all ocean basins” (IPCC, 2012).	**Environmental impacts** - Dispersion and behaviour of air emissions and dust emissions affected **Disruption of mining operations** - Transport and other infrastructure damaged

[37] Note: The category ‘cyclone/typhoon/hurricane’ is considered separately to the categories ‘heavy wind’, ‘heavy rain’, ‘flooding’, ‘heavy waves/storm surges’ in the climate change impact assessment as it is an important and often very destructive phenomenon. The category ‘cyclone/typhoon/hurricane’ always entails the same impacts as ‘heavy wind’, ‘heavy rain’, ‘flooding’, and, if the site under consideration is located closely to the sea, also the category ‘heavy waves/storm surges’.

Climate stimuli and direct climate impact	Description of category	Potential impacts on
		- Workforce capacity reduced due to evacuated or harmed workers -
Sea warming (slow-onset, gradual change)	“Increasing concentrations of greenhouse gases are preventing heat radiated from Earth’s surface from escaping into space as freely as it used to; most of the excess heat is being stored in the upper ocean. As a result, upper ocean heat content has increased significantly over the past two decades” (Dahlmann and Lindsey, 2018). Climate change projections show that “[t]he global ocean will continue to warm during the 21st century. The strongest ocean warming is projected for the surface in tropical and Northern Hemisphere subtropical regions. At greater depth the warming will be most pronounced in the Southern Ocean” (IPCC, 2014: 60).	**Environmental impacts** - Biodiversity stressed (increased sea surface temperatures can be harmful for marine ecosystems which are impacted by offshore mining) **Disruption of mining operations** - No potential supply disruptions due to this climate stimuli/direct climate impact
Permafrost degradation (slow-onset, gradual change)	Permafrost can be defined as a state of the ground (i.e. soil or rock) “that remains at or below a temperature of 0°C for long periods […]. The minimum period is from one winter, through the following summer, and into the next winter; however, most permafrost has existed for much longer” (Natural Resources Canada, 1995). Climate change projections show that “[i]t is virtually certain that near-surface permafrost extent at high northern latitudes will be reduced as global mean surface temperature increases” (IPCC, 2014: 62).	**Environmental impacts** - Reduced integrity of tailing storage facilities **Disruption of mining operations** - Transport infrastructure impacted
Melting glaciers (slow-onset, gradual change)	“Glaciers are ancient rivers of compressed snow that creep through the landscape, shaping the planet’s surface. They are the Earth’s largest freshwater reservoir, collectively covering an area the size of South America. Glaciers have been retreating worldwide since the end of the Little Ice Age (around 1850), but in recent decades glaciers have begun melting at rates that cannot be explained by historical trends” (WWF, n.d.). Climate change projections show that “[t]he global glacier volume, excluding glaciers on the periphery of Antarctica (and excluding the	**Environmental impacts and supply:** see ‘occurrence of flooding’

Climate stimuli and direct climate impact	Description of category	Potential impacts on
	Greenland and Antarctic ice sheets), is projected to decrease by 15 to 55% for RCP2.6 and by 35 to 85% for RCP8.5" (IPCC, 2014: 62).	
Sea-level rise (slow-onset, gradual change)	The most important contributors to mean sea level rise have been "[o]cean thermal expansion and glacier melting" (IPCC, 2014). "[S]ea-level rise occurs gradually. Its impacts may not be immediately seen or coalesce around a single sea-level rise event. Permanent flooding on land is a direct hazard caused by sea-level rise" (UNISDR, 2017). Indirect (secondary) hazards include extended damage caused by storm surges or saltwater contamination of fresh water sources (UNISDR, 2017). Climate change projections show that "[i]t is very likely that mean sea level rise will contribute to upward trends in extreme coastal high water levels in the future. There is high confidence that locations currently experiencing adverse impacts such as coastal erosion and inundation will continue to do so in the future due to increasing sea levels, all other contributing factors being equal. The very likely contribution of mean sea level rise to increased extreme coastal high water levels, coupled with the likely increase in tropical cyclone maximum wind speed, is a specific issue for tropical small island states" (IPCC, 2012: 15).	*In the long term, sea level rise potentially exacerbates the risk of coastal flooding and may have impact on ship loading facilities or mine infrastructure at sea level*.

B Appendix B

Table 26: OekoRess Evaluation scheme for environmental impacts from mining for individual mining examples

Site-related evaluation matrix			
	Field	Goal	Indicator
Geology	Commodity-specific	Avoiding pollution risks	Preconditions for acid mine drainage (AMD)
			Paragenesis with heavy metals
			Paragenesis with radioactive components
	Deposit-specific	Limiting the direct impacts on ecosystems	Deposit size
		Limiting the effort for exploitation	Ore grade
Technology	Mining-specific	Limiting the direct impacts on ecosystems	Mine type
	Processing-specific	Avoiding pollution risks	Extraction and processing method
	Management-specific	Minimisation of risks from mining waste	Mining waste management
		Minimisation of longevity of impacts	Remediation measures
Site (surroundings)	Natural environment	Avoiding natural accident hazards	Accident hazard due to floods, earthquakes, storms, landslides
		Avoiding competition in water usage	Water Stress Index (WSI) und desert areas
		Protection of valuable ecosystems	Protected areas and Alliance for Zero Extinction (AZE) sites
	Social environment	Avoiding environment-related conflicts in resource usage	Conflict potential with local population *(2 Worldwide Governance Indicators)*

Source: Own table, based on Dehoust et al. (2017)

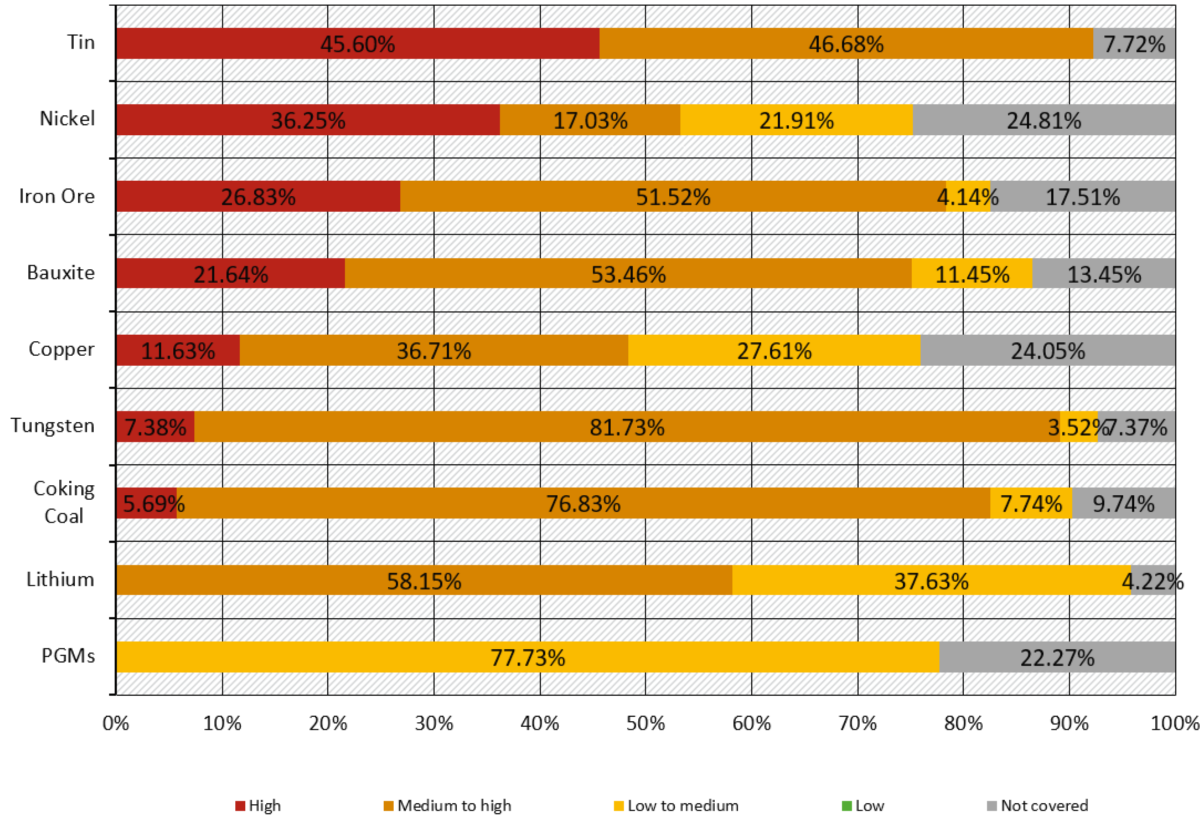
Table 27: Evaluation scheme for raw material-related environmental hazard potential (EHP)

Raw material-related evaluation matrix		
	Goal	Indicator
Geology	Avoiding pollution risks	Paragenesis with heavy metals Paragenesis with radioactive components
Technology	Limiting the direct impacts on ecosystems	Mine type
	Avoiding pollution risks	Use of auxiliary substances
Natural Environment	Avoiding natural accident hazards	Accident hazard due to floods, earthquakes, storms, landslides
	Avoiding competition in water usage	Water Stress Index (WSI) und desert areas
	Protection of valuable ecosystems	Protected areas and Alliance for Zero Extinction (AZE) sites
Governance Environment	Compliance with standards	Environmental governance in major production countries
Value Chaine	Limiting the global extent of EHPs	Cumulated raw material demand of global production (CRD_{global})
	Limiting the global extent of EHPs	Cumulated energy demand of globalproduction (CED_{global})

Source: Own table, based on Dehoust et al. (2017)

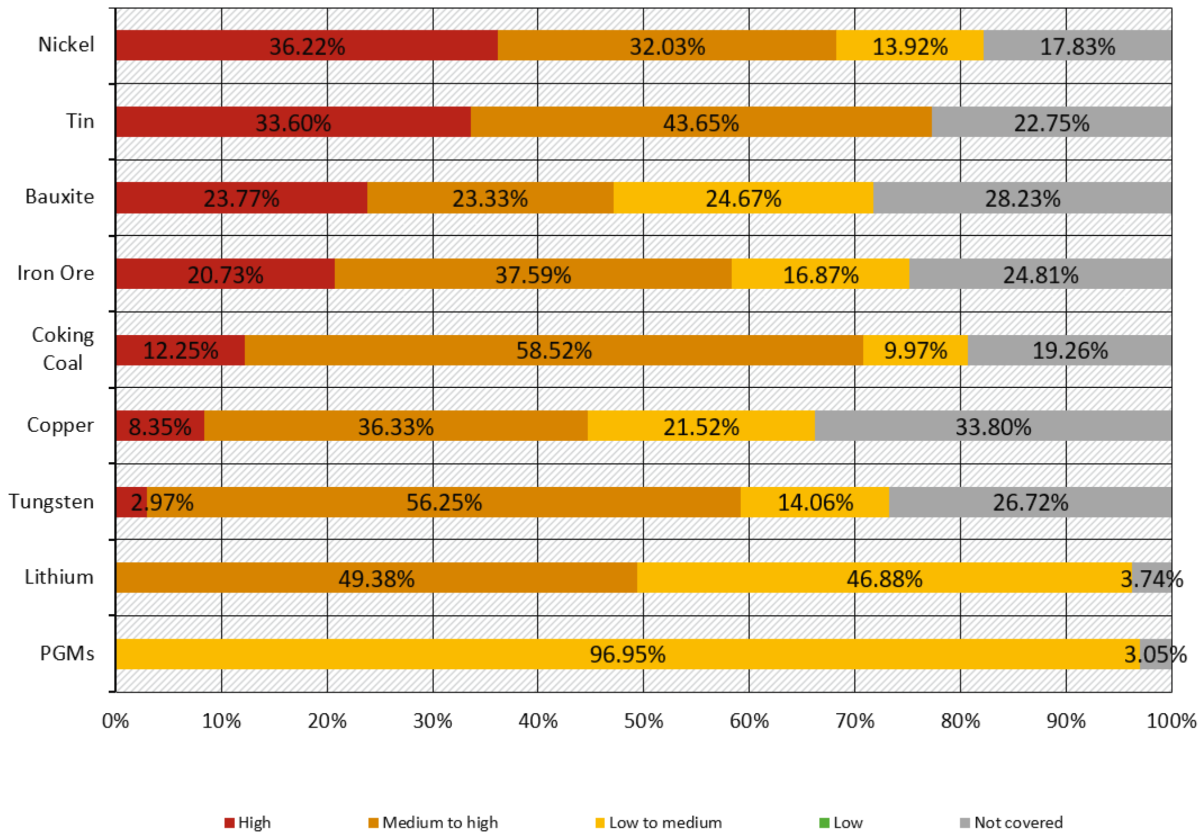
C Appendix C

Figure 16: Comparison of the exposure of producing countries



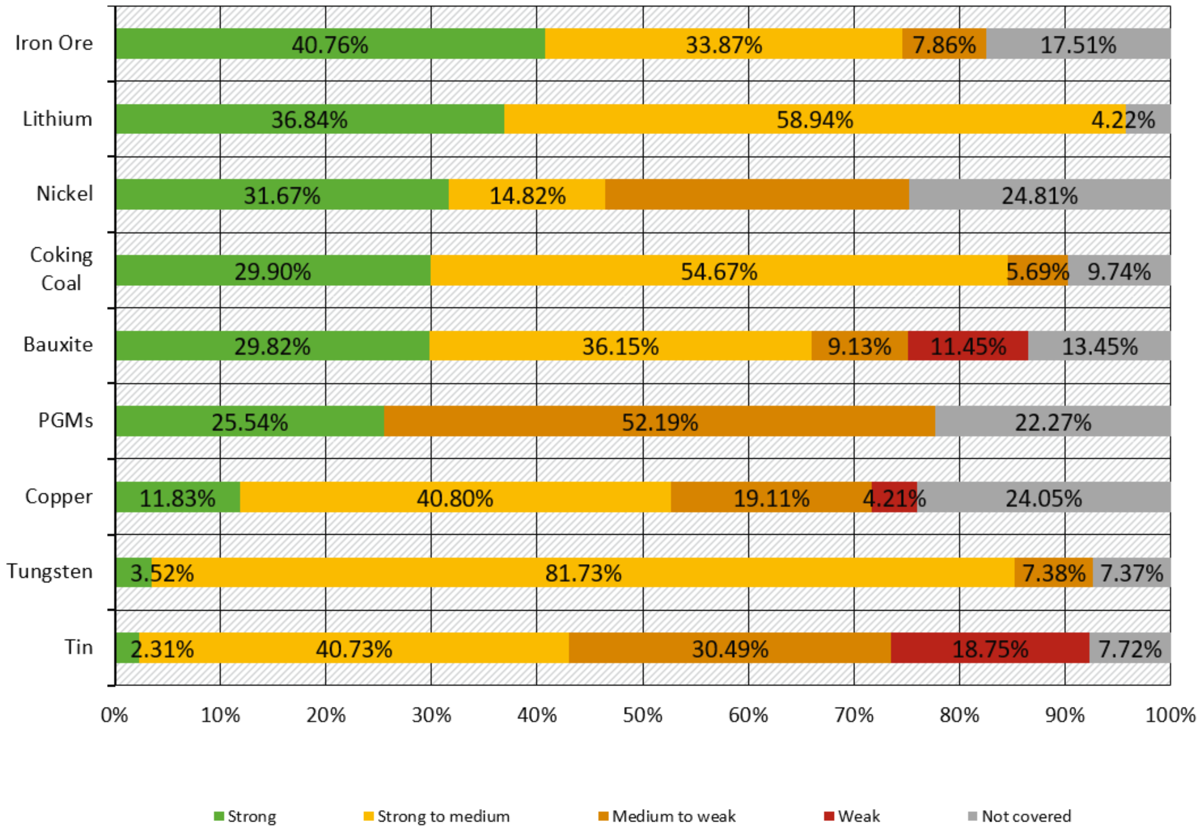
Source: Own figure, results based on USGS (2018), ND-GAIN (2018).

Figure 17: Comparison of the exposure of reserves



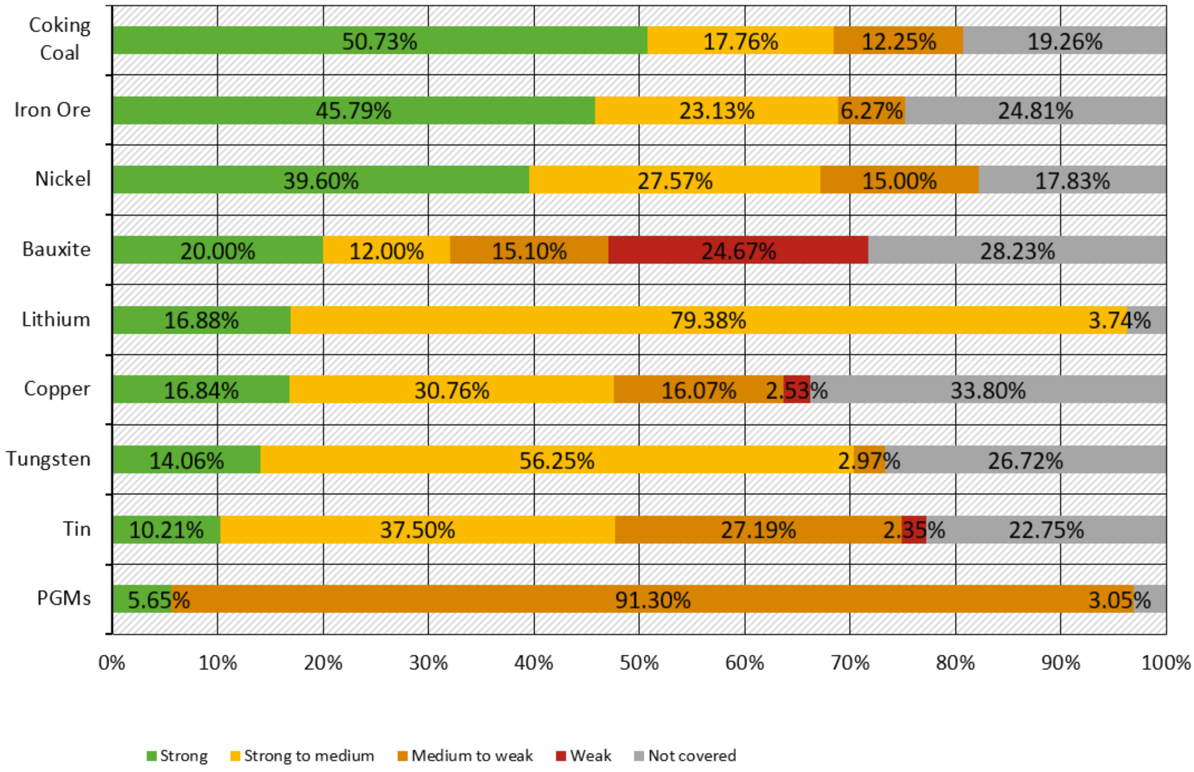
Source: Own figure, results based on USGS (2018), ND-GAIN (2018).

Figure 18: Comparison of the adaptive capacity of producing countries



Source: Own figure, results based on USGS (2018), ND-GAIN (2018).

Figure 19: Comparison of the adaptive capacity of reserves



Source: Own figure, results based on USGS (2018), ND-GAIN (2018)