Abstract

Is the availability of critical materials going to be a bottleneck for the global green transition in the next decades?

This is an essential and strategic question that I aim to answer in this thesis. Since exploration and setting-up new mining projects could take 10-40 years, we need to act and plan to avoid a potential bottleneck for our renewable energy and low carbon technology development in such a green transition. Comparing this lead-time to the time horizon of building the green transition's necessary infrastructure suggests that the last call to inform decision-makers is now.

This thesis analyses two types of resource bottlenecks or supply risks, i.e. a geotechnical and a geopolitical supply risk. In this dissertation, three case studies is used to assess the geotechnical supply risk, using platinum, cobalt, and metals in solar panels as case studies. Two case studies is used to assess the geopolitical supply risk, using platinum and cobalt as case studies. Two aspects, recycling and substitution are used to assess how to mitigate potential supply risks. The geotechnical supply risk comprises the risks that physical/technical resource availability or planning of mining and extraction can cause a shortage. The geopolitical supply risk concerns the risk that political aspects in regions or countries behind key resource supplies can cause a shortage. This can be the case, if some countries or companies want to use their production market share to exercise market power, or if the primary producer must lower their production due to e.g., strikes, cartels, embargoes, wars, or mining accidents. To understand and mitigate the risk of such potential supply shortages, we need to forecast the demand of metals and other resources required in low-carbon technologies and to compare this demand to the geotechnically available metal supply in the same time horizon, and we need to analyze the geographical distribution of future supply and reserves and the potential geopolitical supply risk related to these locations.

With a high global market share of battery electric vehicles or fuel cell vehicles in several global road transport scenarios, the forecasted demand for platinum and cobalt for these low carbon technologies is found to surpass the current reserves for platinum or cobalt. Accumulated platinum demand could reach 51,000 tonnes in the highest demand scenario in 2050, while current reserves are reported to be app. 34,000 tonnes. For cobalt, the accumulated demand could reach 15,000 kt, while current reserves are 7,000 kt. However, although current reserves and resources do not seem sufficient, it does not necessarily mean that the metal will be in shortage, because the reserves and resource numbers are dynamic. But it does mean that there is a risk in the near term. A methodology has been proposed to analyze the minimum and maximum range of how metal reserves will develop, based on estimations of current resources and undiscovered resources. For platinum, I found this range spanning from 25,000 to 80,000 tonnes in 2050. Comparing this range of geotechnical available reserve with future estimated demand suggest that platinum's global availability may well be sufficient for the green transition with respect to these technologies, even with a high global market share of fuel cell vehicles. It is difficult to make final conclusions because technological development keep changing the exact numbers for both supply and demand.

Existing estimates of undiscovered deposits mainly focus on gold, copper, and PGM, except for one study for Finland. This means that for many metals it is almost impossible to judge if there is enough metal in the ground to satisfy our future global primary demands. For studies focusing on other metals,

the new goal is then to provide early warnings of potential future supply bottlenecks in order to allow decision makers sufficient time to mitigate the bottlenecks.

Future demand for cobalt, copper, dysprosium, gallium, indium, lithium, neodymium, nickel, selenium and tellurium was extracted from literature and compared to presently known reserves and resources. Of these metals, tellurium was found to have the highest risk of being in shortage, followed by indium, nickel, selenium, and cobalt. The 2018 estimations of the six remaining metals' resources seem to be plenty to cover the predicted demands to 2050.

In modern history, geopolitical issues have been the main reason for the three known cases of global metal shortages. First, cobalt was in shortage due to a civil war in Congo in the 1970s. Second, Russia decreased its export of palladium in the 1990s. Third, China halved its export of rare earth elements around 2010. Analyzing the geopolitical risk of platinum based on trade patterns and recycling potentials shows that Europe has the most diversified trade partners network. This gives Europe the lowest supply risk globally, followed by Japan. Europe is both a trading hub, mainly through Switzerland, and a recycling hub, mainly through Germany and Great Britain, for platinum, whereas Japan mainly recycle its own waste. North America and China almost rely 100 % on importing raw platinum, since China does not have that many platinum containing products reaching end of life yet, and North America is exporting the majority of their waste containing platinum. Analyzing the supply risk of cobalt with information of the national affiliation and ownership of mining companies shows that the US, EU, and China reduce their supply risk significantly by investing in mines in foreign countries, where Japan and the Rest of World do not.

Recycling is essential to lower the geopolitical supply risk, reduce the demand for primary metal, and increase the diversity of a region's trade partners. The platinum case studies show that it is possible to obtain a high recycling rate globally, but for many metals and rare earth elements, the recycling rate is very low or even absent today. Recycling can be ensured by the market economy or by legislation, and today only high volume bulk metals and precious metals have a high recycling rate for economic reasons. Often, costs and structure of waste collection and recovery are barriers. For example, in the case of remote-located solar panels the missing structure and lack of organised waste collection system were found to be a barrier to economically motivated recycling. Up to 36% of installed solar panels in the West African region is located off-grid, and the example indicates that legislation is needed to secure a high recycling rate for metals with a too low value or too high collection cost.

Being able to substitute one metal with another can mitigate global shortages, but substitution often comes at the cost of less efficient or more expensive technologies. To assess for which metals substitution can mitigate a shortage, I created an overview of the 1) substitutes performance in all end uses of 17 selected metals and 2) the criticality of all the substitutes, both on 3) an elemental level and 4) a product/service/concept level. Based on this overview a substitution criticality score was made for the 17 metals. Combining the analysis of substitutes criticality with the study of demand versus current reserves and resources suggests that the most critical metals are tellurium, indium, selenium, and cobalt, since they all have relatively high substitution criticality score and their current reserves might not be enough to cover future demands with the present understanding of the demand-side in future energy technologies.