Material Criticality for Future Telecommunication Technologies

Scenario Development and Supply Chain Resilience Strategies
A Case Study for a Dutch Telecommunication Company

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Abstract

Digital technologies are enablers for a variety of sustainable use cases. The underlying infrastructure for this digital transformation is provided by telecommunication companies through their future technologies. Future telecommunication technologies consist on a variety of raw materials, amongst some are considered to be critical. Critical Raw Materials (CRMs) are associated with a high economic importance, as well as severe supply risks.

The goal of this research was to firstly identify which CRMs are contained in future telecommunication technologies and secondly how the demand for them will develop until 2030 or 2050 under slow, fast and full rollout scenarios and compared to current supply levels. Based on that, thirdly strategic choices for telecommunication companies on creating a resilient supply were given. The design of the study was build up in the respective order and was based on a case study research for a Dutch telecommunication service provider and expert interviews with technology suppliers and research institutes in the network.

The focus technologies included 5G Technologies, Photonics, Edge Computing and Quantum Technologies. The general finding was that a broad range of CRMs could be identified in the network equipment of these technologies, with the CRMs Erbium, Gallium, Germanium, Phosphorous, Silicon and Titanium having the highest frequency of occurrence. Amongst them, Erbium has also very high supply risks. When looking at the demand development for CRMs contained in future telecommunication technologies, an 8-fold increase under a slow rollout scenario until 2030, a 15-fold increase under a fast rollout and a 16-fold increase under the full rollout scenario could be identified. The demand by far comes mostly from 5G Technologies. When comparing the future demand with current supply, specifically 14 CRMs could be identified where demand will exceed supply: Beryllium, Natural Graphite, Dysprosium, Gallium, Germanium, Magnesium, Neodymium, Palladium, Ruthenium, Tantalum, Terbium, Titanium, Thulium and Yttrium. From this is could be concluded that if supply cannot meet demand, the future rollout of these technologies is at stake resulting in company's corporate strategies being at risk and thus the future of the telecommunication industry and a global digital transformation.

In order to tackle these bottlenecks of demand and supply, there are strategic choices companies can chose for creating supply chain resilience for material criticality. Supply risks mitigating strategies included the design of technologies after eco-design principles, increase recycling rates, investigate into substitution potential, diversity supply geographically as well as ownership based, avoid conflict minerals by responsible sourcing, stockpiling, lobbying for new mining activities, foster cross-chain collaboration and redesign whole business models after circular economy principles. All of these strategies can be strategic choices for telecommunication companies and are advised to be considered at the company level.

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Abbreviations

Compound Annual Growth Rate	CAGR
Critical Raw Materials	CRMs
Electric Vehicle	EV
End of Life	EOL
Heavy Rare Earth Elements	HREEs
Information and Communication Technology	ICT
Light Rare Earth Elements	LREEs
Original equipment manufacturers	OEMs
Photonic Integrated Circuits	PICs
Precious Group Metals	PGMs
Quantum Key Distribution	QKD
Radio Access Network	RAN
Rare Earth Elements	REEs
Remote Radio Unit	RRU

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Chapter 1: Introduction

From smart and efficient energy management (Huawei, 2020), remote health care by artificial intelligent human robots, optical measurements for improvements in air quality and emission monitoring (National Agenda Photonics, 2018) to safe and reliable autonomous driving aiming for a reduction of mobility needs (European Commission, 2020c) – Digital technologies are enablers for a variety of sustainable use cases in the future we are going to live in. Additionally, the importance of digital technologies can also be found on national agendas, such as the European Union aiming for achieving not just a competitive advantage, but even sovereignty over them (European Commission, 2020a) and the United Nations General Assembly (2016) adopting a resolution for the internet being a human right, to which everyone needs to have access to.

The telecommunication industry has a huge influence on the world and acts as the central changemaker for a digital transformation. Future telecommunication technologies, such as 5G Technologies, Photonics, Edge Computing or Quantum Technologies are needed for realizing this transformation (KPN, 2020). It is expected that 20% of all global connections will be covered by 5G until 2025 (GSMA, 2020) or that Photonics in its best case fully replaces electronics (Professor A for Photonics Integration, 2021). And also Edge Computing and Quantum Technologies are expected to have a vast deployment.

Such future technologies consists of different equipment types that will be implemented in the physical network infrastructure of telecommunication companies (KPN, 2020). This equipment is manufactured using a broad range and large quantity of different elements with unique physical properties and is coined by fast technological advancements (Ku, 2018; Graedel et al., 2015). Hence, the demand for raw materials contained in such equipment is coming from a variety of materials and is likely to increase in the future with technology rollout. However, there is one aspect associated with such raw materials that might constrain the unlimited access: *Material Criticality*.

Material criticality is defined as potential risk arising from globally spanned supply chains against vulnerabilities arising from the importance of a material (Hofmann et al., 2018). Practically, this means that the sourcing of specific raw materials might be constraint due to environmental and social implications, geopolitical influences, price volatilities or market and supply chain aspects (Griffin et al., 2019; Kolotzek et al., 2018).

These criticality reasons might constrain the resources we really have accessible for rolling out future telecommunication technologies. In return, in the case that the telecommunication industry does not have access to the required raw materials, future technologies cannot be rolled out and a digital transformation including sustainable use cases cannot be implemented. However, in order to find solutions for this dilemma, firstly the actual contained Critical Raw Materials (CRMs) need to be identified and demand developments need to be investigated into. Secondly, the arising demand needs to be compared to the current situation of supply in order to draw conclusions on potential bottlenecks. Lastly, strategic choices for telecommunication companies need to be identified, which can create supply chain resilience for those CRMs contained in future technologies. Thus, the main research question is the following:

Which strategic choices do telecommunication companies have to secure supply chain resilience for Critical Raw Materials contained in future technologies?

The research approach includes a case study based on the Dutch telecommunication company KPN. The equipment of future technologies that KPN is developing together with supply chain partners form the base of this research. However drawn conclusions will also hold valid for the whole telecommunication industry.

Chapter 2: Problem Definition

The following subchapters include the theoretical background, the research gap, the goal and scope of the study as well as the study structure.

2.1. Theoretical Background

The theoretical background includes defining the most important concepts for this study. Furthermore, it pictures the before conducted literature research on CRMs contained in future technologies in the telecommunication industry.

2.1.1. Material Criticality

Material criticality is defined through different indicators within a criticality assessment based on raw materials contained within an entity. These determine on whether a raw material is considered to be *critical*. Criticality assessments can be conducted through the perspective of a product, technology, company or a regional level (Schrijvers et al., 2020). Different research was conducted on different aspects of criticality:

Kolotzek et al. (2018) proposes a framework, that quantitatively assesses the criticality of materials on a company-level, focusing on three dimensions and 11 indicators: Firstly the supply risk dimension triggered by concentrations, demand changes, political landscape and supply reduction. Secondly, the environmental dimension with ecosystem quality and human health. Thirdly, the social dimension with local community, society and workers as indicators. All different risks include several sub-indicators that are later weighted and calculated to retrieve a final criticality number. Furthermore, according to Kolotzek et al. (2018), the crucial steps from the company side are to conduct a vulnerability analysis, followed by a content identification, the assessment through the above described framework and the interpretation of the outcome from the companies perspective.

This research is followed by Griffin et al. (2019), who reviewed 42 criticality studies and further developed an assessment: The six major risk categories found through the literature review include scarcity, geopolitics, demand, environment, supply chain, market and social were defined by establishing several sub-indicators. Additionally, the risk categories product concept viability, production and profitability were added (Griffin et al., 2019). Further aspects of these CAs, however without direct focus on the company level include the following: Achzet et al. (2013) investigated the evaluation of raw material supply risks, including the indicators country concentration and risk, by-product dependence, depletion, company concentration, growth in demand, recyclability, substitution, import dependences or prices for commodities. Helbig et al. (2016) investigated the evaluation of raw material vulnerabilities, including the indicators substitutability, product value, future demand, strategic importance, material value and spread of utilization. Graedel et al. (2012) investigated environmental implications through a CA. Schrijvers et al. (2020) further provides an overview on the current state of indicators included in material criticality assessments.

Iaonnidou et al. (2019) focuses on summarizing research about dynamic CAs, including the temporal scope. Here especially the indicator “strategic importance of resources” have a focus on the assessment of future technologies (Iaonnidou et al., 2019). Furthermore, Habib et al. (2016), Riddle et al. (2015) and Moss et al. (2011) focus on the temporal aspect as well.

This shows that there is a large variety of indicators that are contributing to whether a material is considered to be *critical*. The following Figure 2.1 gives a summary on the above.

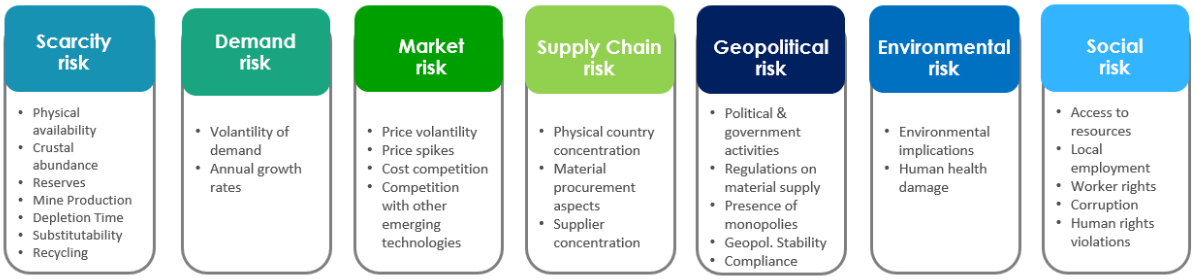


Figure 2.1: Overview on supply risks triggering material criticality

As part of this study, the CRM list of the European Commission (2020b) will be used. The two main indicators the European Commission (2020b) analyzed include supply risk and economic importance of a raw material to the European economy. The supply risks were calculated based on global and European supply concentrations, country governance, import reliance, trade restrictions, supply chain bottlenecks, the end-of-life (EOL) recycling rate and a substitution index (European Commission, 2020b). The economic importance is calculated including also substitutes in terms of cost and performance and influenced by value added from sectors (European Commission, 2020b). The list of CRMs is updated every three years, while the taken list represents the year 2020 (European Commission, 2020b). Conducting this assessment based on supply risks and economic importance resulted in a variety of different elements and materials results in the following outcome as shown in Figure 2.2.

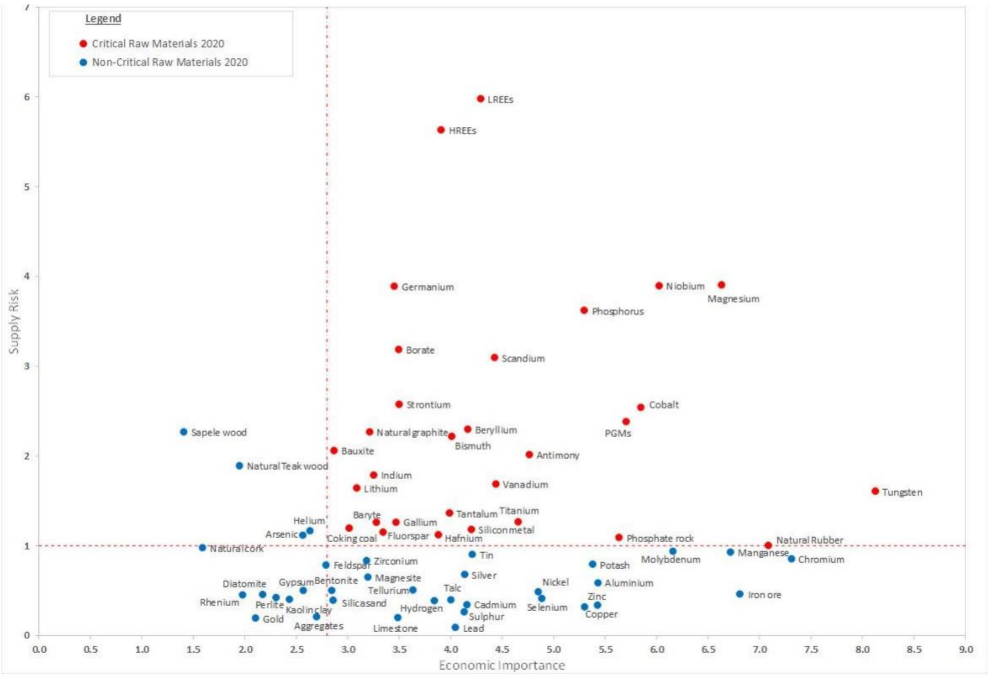


Figure 2.2: Outcome of the criticality assessment on raw materials of the European Commission (2020b).

The following Figure 2.3 shows the CRMs as part of the Periodic Table of Elements. This is the underlying list of this study.

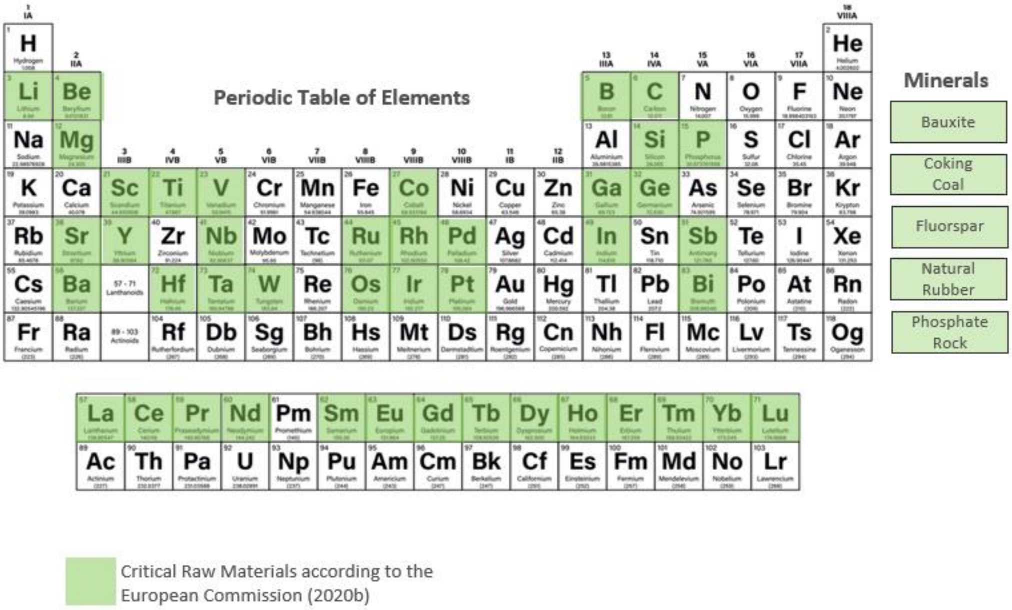


Figure 2.3: Critical Raw Materials defined by the European Commission (2020b)

Moreover some CRMs are clustered into groups. This is firstly the case for Precious Group Metals (PGMs), consisting of the CRMs Ir, Pd, Pt, Rh and Ru. Additionally Rare Earth Elements (RREEs) are clustered into light RREEs, including Ce, La, Nd, Pr and Sm and heavy RREEs, including Dy, Er, Eu, Gd, Ho, Lu, Tb, Tm, Yb and Y.

2.1.2. Background of Critical Raw Materials for Future Telecommunication Technologies

Focusing on literature, which includes projections on the use of CRMs in future telecommunication technologies, only very little literature could be identified. The EU Foresight Study (2020) was taken as a starting point and snowballing was conducted to identify related literature. Additionally, due to the fast pace of changing predictions within digital technologies, only literature published within the last five years was taken into account.

The 2020 published Foresight Study of the European Commission (2020a) investigates raw material flows for different future sectors. One of the focus sectors include digital technologies. The European Commission (2020a) considers CRMs as especially crucial for information and communication technology (ICT) devices. Digitalization is fostering the need for storing data in data centers, network infrastructures and endpoints, leading to increased demands for materials for the production of memories (European Commission, 2020a). Additionally, future demand for ICT materials will be influenced by the need for IOT devices and fiber optics, the miniaturization of lower level components, plans against obsolescence, restrictions on e-waste exports and the economic side of making materials cheaper (European Commission, 2020a). Within digital technologies, the whole periodic system of elements can be found (European Commission, 2020a). Demand developments and the importance of single CRMs vary a lot (European Commission, 2020a). For example for the CRMs Pd, Ga, Dy and Nd, used in ICT devices, demands could either stagnate or rise (European Commission, 2020a). In the case of In, growth is predicted, since no recycling technologies are in place, neither can it be substituted, however used extensive in digital technologies (European Commission, 2020a; Ciacci et al., 2019). Contrary, it is also argued that ICT devices have the potential of being an enabler for a more efficient CRM consumption, by changing productions exemplarily (European Commission, 2020a; Widmer et al., 2013; Bonilla et al., 2018). Finally, another crucial point mentioned is that digital security becomes increasingly important which can also have impacts on the use of ICT devices and thus CRMs (European Commission, 2020a; Polverini et al., 2018). Moreover, the European Commission (2020a) also rises awareness on the fact that different sectors will also compete for CRMs, especially for B, Ga, In, RREs, Co, Nb and Si. Lastly, the European Commission (2020a) mentioned that especially REEs will be contained in future digital technologies.

As part of the EU SCRREEN initiative, several studies were conducted: Tercero Espinoza et al. (2019) investigated the raw materials Co, Ga, In, Mg, Nb, PGMs, phosphate rock, RREs, W and Ta in order to identify their use in future applications. The outcome of the study included that for ICT and telecom technologies, the demand for CRMs can either stagnate in the case of In for screens or continue to increase in the case of REE, Ta, Pd for electronic devices and Ge for optical fibers (Tercero Espinoza et al., 2019).

Also as part of the EU SCRREEN initiative Monnet et al. (2018) investigated into the sector of electronics and telecommunication in order to identify future trends of CRMs. For the application within the telecom sector, only silica and non-silica fiber optics were assessed (Monnet et al., 2018). Only focusing on Germanium in silica fiber optics, the outcome of the study was that the Germanium demand will rise to 120 tons globally by 2035, which is double the amount as of today (60t) (Monnet et al., 2018). Additionally a PESTEL analysis was conducted.

Ku (2018) investigated into impacts on supply chains and market dynamics arising from emerging data storage technologies. Among the findings were that materials demands for most memories is predicted to be little compared to the current state of the art (Ku, 2018). However, specific memory types can also have larger impacts on Nd, PGMs, Ge and Ha (Ku, 2018).

The Deutsche Rohstoffagentur (2016) analyzed emerging technologies regarding their material criticality until 2035. In general, they predicted the Industry 4.0 requiring an extensive amount of materials, from which some are critical, such as Li, Sc, Ta or Ge (Deutsche Rohstoffagentur, 2016). Additional, in the information and communication technology sector, materials were identified: Sn, Ag, Cu, Bi, Zn, In, Ni, Ge, Au, Pt, Sb for lead-free solders; Ag, Cu, Al (antennas); Si (chips) for Radio Frequency Identification, In, Sn, Sb for In screens; V, Li, Nb, Pb, Ge, La, Sc, Nb, Ta for infrared detectors, Ga, In for LED lighting; Ge for fiber cables; Ta, Nb, Mn, Sb, Ag, Pd, Ni, Ti, Sn, Ba for microelectronic capacitors and Ga, As, Ge, Cd, Te for high performance microchips (Deutsche Rohstoffagentur, 2016).

Patrahau et al., (2020) looked into digital technologies and concluded that critical materials are of importance due to a variety of materials being used in electronics to achieve required magnetic or optical properties, meaningful volumes due to increased use of chips and electronic devices and also technology speed impacting supply chains. The CRMs B, Co, Dy, Ga, Ge, Graphite, In, Li, Nd, Pa, Si, Ta and W were considered crucial for digital technologies (Patrahau et al., 2020).

In July (2021) the Deutsche Rohstoffagentur published another study on raw materials contained in future technologies. Relevant for telecommunication companies, these include telecommunication infrastructure technologies Photonics, optical fiber cables, 5G and 6G, as well as data centers (Deutsche Rohstoffagentur, 2021). In the case of Photonics, emphasis was put on a Photonics Transceiver, which includes the CRMs GaAs, InP, GaSb and GaN as part of their laser (Deutsche

Rohstoffagentur, 2021; Sweeny et al. 2017), InGaAs for InP-Wavers, Si and Ge for diodes, InP and Si for different Photonic Integrated Circuits (PICs) and SiN, SiO_2 and $LiNbO_3$ for Si PICs (Deutsche Rohstoffagentur, 2021). Looking at the demand increase until 2040, Deutsche Rohstoffagentur (2021) predicts that Ga and As are not expected to increase significantly, however the demand for In will triple. In the case of glass fiber cables, which is required at the backbones of telecommunication networks, depending on the application and cable type, the following raw materials could be identified: SiO_2, GeO_2 and P_2O_5, (Deutsche Rohstoffagentur, 2021). Furthermore, according to Deutsche Rohstoffagentur (2021), the annual demand for Ge will be between 237t – 277t until 2040 depending on the scenario. Within different network parts for 5G (6G) equipment, the following CRMs were identified by Deutsche Rohstoffagentur (2021): GaAs, $LiNbO_3$, $LiTaO_3$, GaN and InP. For the demand for raw materials for frequency filters in 2040, very different numbers were estimated (Deutsche Rohstoffagentur, 2021): Ga will have an expected demand between 49-90 tons, Li between 15-22 tons, Nb between 12-18 tons and Ta between 356 – 531 tons. Ga demand coming from equipment in base stations is expected to be between 1,6-2,4 tons until 2040 (Deutsche Rohstoffagentur, 2021). Lastly, within data centers different equipment types were analyzed and overall, the following CRMs were identified to be contained: Co, Pt, Ru, Nd, Si and Ta (Deutsche Rohstoffagentur, 2021). For the individual CRMs, the demand is expected to increase until 2040 like the following: Co (37 – 1.479 tons), Pt (20 – 813 tons), Ru (33 – 592 tons), Nd (44 – 9.220 tons) and Ta (48 – 649 tons).

When looking at the overall field of CRMs, research mostly focuses on identifying CRM demand development contained in low carbon technologies of the energy transition, such as solar PV, wind power or electric vehicles (Watari et al., 2019). Watari et al. (2019) conducted a literature review and some of the CRMs identified were Dy, In, Li, Nd, Ge, Co, La, Pt and Ru (de Koning et al., 2018; Grandell et al., 2016; Månberger et al., 2018).

To put the whole matter in a nutshell, generally to my knowledge rather little research was conducted on the future demand of CRMs contained in telecommunication technologies. Furthermore, not clear distinction between what telecommunication technologies entails could be identified, since some studies focused on digital technologies or ICT equipment, which partly belongs to telecommunication technologies.

2.2. Research Gap

A research gap around future telecommunication technologies in the field of tension between material criticality, arising raw material demand and associated supply could be discovered. Firstly, there is a lack of research on CRMs contained in the future equipment of emerging technologies of the telecommunication industry. Secondly, there is a lack of research regarding the CRM demand, those emerging technologies will cause in the future and how this compared to the available supply. Thirdly, there is a lack of research on how specifically telecommunication companies can build up supply chain resilience, given the fact that they are not manufacturing devices themselves, but are providing a service.

2.2.1. Research Questions

In order to close the research gap and to contribute to research on CRM demand arising from the telecommunication industry and the mitigation of potential bottlenecks, the following main research question will be answered as part of this study:

Which strategic choices do telecommunication companies have to secure supply chain resilience for Critical Raw Materials contained in future technologies?

The sub research questions include the following

(1) *Which Critical Raw Materials are contained in the equipment of future technologies of the telecommunications industry?*
(2) *How does the demand for Critical Raw Materials contained in future telecommunication technologies develop compared to current supply?*
(3) *Which strategic choices do telecommunication companies have to secure supply chain resilience for Critical Raw Materials?*

2.2.2. Research Approach

The research approach contains three phases, that build on each other. The first part contains the definition of the focus future technologies and the associated equipment. This requires investigating into the material-related impacts of those technologies and the identification of the raw material occurrence and associated supply risks. The second part contains the development of demand scenarios based on CRMs contained in future equipment after slow, fast and full rollout scenarios. Furthermore, it also includes putting demand into perspective of current supply. The last phase is to identify potential strategic choices for supply chain resilience, telecommunication companies could choose. The below Figure 2.4 gives an overview on the research approach.

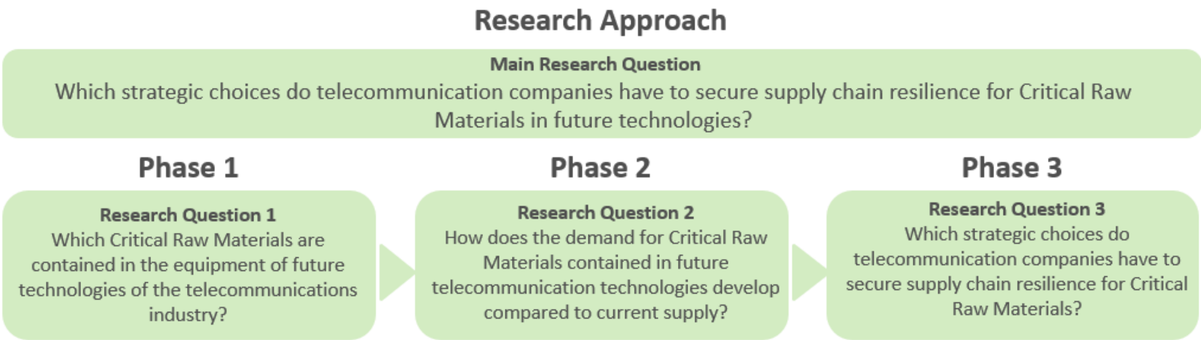


Figure 2.4: Research approach of this study.

2.2.3. KPN – The Case Study

KPN is the biggest telecommunication provider in the Netherlands (KPN, 2020a). The KPN network includes the fixed and mobile network, as well as cloud solutions (KPN, 2020b). The services provided by the KPN network are voice post-paid, mobile data, broadband, as well as TV & media (KPN, 2020c).

KPN is considered to be among the five most sustainable telecommunication companies and 10% sustainably best performing companies globally according to the Dow Jones Sustainability Index (KPN, 2020d). Focusing on that, KPN is committed to the following targets (Personal Communication KPN, 2020):

- 2025: 100% circular operations
- 2030: Fossil-free vehicle fleet
- 2030: 55% energy reduction compared to 2010

- 2040: Reduction of supply chain emissions by 50%

In the domain of CRMs, an earlier study was conducted at KPN. This study had the goal of developing a criticality assessment framework for service providers (Kleinmagd, 2020). Through this assessment, it was identified that for KPN, especially Ga, Rh, the REEs, Mg, Si, Bi, In and V are considered moderately to highly critical (Kleinmagd, 2020). Based on those findings, risk mitigation strategies were developed for KPN internally, to the tier 1 supply chain as well as the whole supply system for materials (Kleinmagd, 2020).

2.3. Goal and Scope of the Study

This purpose of this study was to contribute to a solution for the problem of material criticality for the telecommunication industry. Focus was solely put on future technologies with an impact on the physical infrastructure of the telecommunication network. Even though there might be a huge variety of also smaller future technologies, selected technologies represent major trends that can currently be observed within telecommunication companies. The research is solely limited to CRMs and excludes all other raw materials, even though demand might also be high for them. However, depending on the data availability, other raw materials will be mentioned within this study, but not further assessed.

As a temporal scope, a baseline year of 2021 was chosen. Developed scenarios will depend on a most likely rollout date, which was set to either 2030 or 2050. As a geographical scope, all developed conclusions refer to the whole world and calculated numbers represent global demand or supply. This was done in order to draw conclusions for the whole telecommunication industry.

The duration of this study started with data gathering in October 2020 and lasted until July 2021. Data gathered was mainly based on experts in the network of the Dutch telecommunication company KPN, with some exceptions of experts inside and outside the KPN network from Austria, Germany, the United Kingdom and the United States.

2.4. Structure of the Study

Chapter 1 and 2 include the introduction into the research topic and the theoretical background and research gap. Chapter 3 gives an overview on the research methods of the three phases of the study. Detailed explanations will be given on the different methodological steps that were taken. Chapter 4 represents the first findings of this study, including the CRMs contained in different network equipment. It is also important to mention, that a color scheme is kept throughout the report with each color (purple, yellow, blue and red) representing one technology. Chapter 5 represents the scenario development of the demand arising from CRMs used in future technologies. It furthermore contains comparisons between the demand of 2021 and under different scenarios. Chapter 6 shows the comparison of the demand under different scenarios with the currently accessible supply. Chapter 7 represents a summary of supply chain resilience mitigation strategies and how they can be applied to telecommunication companies. Chapter 8 includes a discussion on the research findings, the limitations of the study and future recommended research. Chapter 9 is the conclusion.

Chapter 3: Research Methods

The below Figure 3.1 gives an overview on the research methods used per phase. Additionally, in the sub-chapters, detailed explanations on the methods can be found.

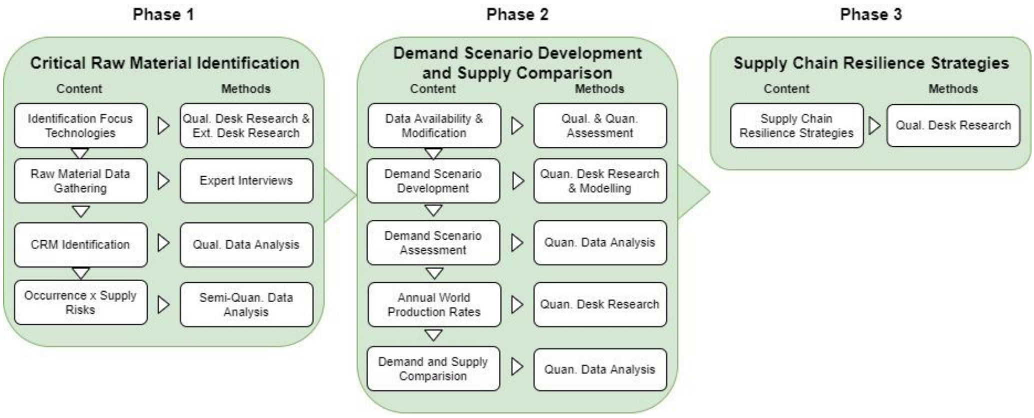


Figure 3.1: Methods Overview

3.1. Critical Raw Materials Identification

Below explanations include detailed descriptions Phase 1 as shown in the above Figure 3.1.

Identification Focus Technologies: Qualitative KPN Desk Research and External Desk Research

Desk research includes working on data that has already been collected and processed before (Moore, 2018). Especially literature reviews and the analysis of already existing data sets counts towards that (Moore, 2018). The first step was to identify focus technologies. The decision on which future technologies to select was based on important technologies to KPN's business and those technologies that have an impact on the network infrastructure and thus on the raw material usage.

Raw Material Data Gathering: Qualitative Internal and External Desk Research & Semi-Structured Interviews

For the identification of future equipment, the corresponding lower level components, raw material contents and weights, a combination of desk research and semi-structured interviews was chosen. Semi-structured interviews are coined by the collection of structured information while also gathering information about beliefs or attitudes (Moore, 2018). This can include closed questions with limited answer options or open questions (Moore, 2018). Additionally, as mentioned above, the analysis of already existing data sets was included as well (Moore, 2018).

The first step included the identification of points of contacts within the network of KPN, who are experts in the field of the technologies. These can include research institutes, suppliers, device manufacturers or internal experts.

The second step was to reach out to the experts via e-mail to ask for an interview. This process included two crucial steps. An introduction e-mail about the topic of material criticality and its connection to the future telecommunication technologies was written, including the explanation of what was the goal of reaching out. Additionally, a power point presentation about the topic was attached, giving an overview on the meaning of material criticality, the before conducted work on material criticality at KPN done by Kleinmagd (2020) and the presentation of several examples of CRMs contained in ICT equipment. The second step was to conduct the semi-structured interview with the respective experts through a mostly 60 minute brainstorming session on which CRMs are contained in different lower level components and which weights these CRMs do have in the respective lower level component. Simply the open question on “Which CRMs are contained in this network equipment and how much do they weight?” was posed. Moreover, it is important to mention that snowballing was used for gathering the required data. In most of the cases, experts knew other points of contacts that were experts in other devices or lower level component. With a recommendation of the first expert it was reached out to the second expert to further gather data on raw material contents of other lower level components.

CRM Identification: Qualitative Data Analysis

For the decision on which raw material is a CRM, a basic approach was followed. The CRM list of the European Commission (2020b) was taken and it was double checked on whether a raw material was contained in the list. The reason for that is that this case study is based on a Dutch telecommunication company, which thus is mostly influenced by European CRM aspects. The list can be found in Chapter 2.1.1.. In case a raw material was not considered *critical*, it was excluded from the further steps. The goal was to create comprehensive overview graphics that show CRMs contained in future telecom equipment of the focus technologies.

Occurrence X Supply Risk Assessment: Semi-Quantitative Data Analysis

As a last step, a semi-quantitative data analysis was conducted with the goal of identifying which CRMs do occur the most often and are in the same time associated with the highest supply risks across the different future technologies and equipment types. In order to do so, the data was analyzed after the following points

- Frequency of occurrence of a CRM across different equipment types per technology
- Frequency of occurrence of a CRM across different future technologies

and was mapped after the following numbers retrieved from the European Commission (2020b). The raw data should look like the following Table 3.1.

Table 3.1: Raw data for the occurrence x supply risk assessment.

	SR	Occ.		SR	Occ.		SR	Occ.		SR	Occ.
Antimony Sb	2.0		Gallium Ga	1.3		Palladium Pd	1.3		Thulium Tm	6.1	
Barium Ba	1.3		Germanium Ge	3.9		Phosphorous P	3.5		Titanium Ti	1.3	
Beryllium Be	2.3		Hafnium Hf	1.1		Platinum Pt	1.8		Tungsten W	1.6	
Bismuth Bi	2.2		Holmium Ho	6.1		Praseodymium Pr	5.5		Vanadium V	1.7	
Boron B	3.2		Indium In	1.8		Rhodium Rh	2.1		Yttrium Y	4.2	
Natural Graphite C	2.3		Iridium Ir	3.2		Ruthenium Ru	3.4		Ytterbium Yb	6.1	
Cerium Ce	6.2		Lanthanum La	6.0		Samarium Sa	6.1		Bauxite	2.1	
Cobalt Co	2.5		Lithium Li	1.6		Scandium Sc	3.1		Coking Coal	1.2	
Dysprosium Dy	6.2		Lutetium Lu	6.1		Silicon Si	1.2		Fluorspar	1.2	
Erbium Er	6.1		Magnesium Mg	3.9		Strontium Sr	2.6		Natural Rubber	1.0	
Europium Eu	3.7		Neodymium Nd	6.1		Tantalum Ta	1.4		Phosphate Rock		

The supply risk data was taken from the methodology of the European Commission (2020b) and the occurrence data needs to be filled out after the research findings. Lastly, data will be presented in the following coordinate system, as shown in Figure 3.2.

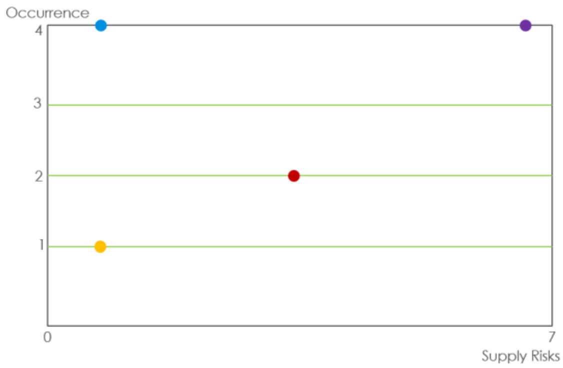


Figure 3.2: Occurrence x Supply Risk matrix for the assessment of supply risks per frequency of occurrence of CRMs.

In the above case, it could be concluded that the blue dot would represent a occurrence in four out of four technologies, but low supply risks. The purple dot can be considered problematic, since it is occurring in each of the four technologies, while also being associated with very high supply risks.

3.2. Critical Raw Material Demand Scenarios and Supply Comparison

Below explanations include detailed descriptions Phase 2 as shown in the above Figure 3.1.

Data Availability & Modification: Qualitative and Quantitative Assessment

Before aggregating the gathered data to single weights per CRM, a qualitative and quantitative assessment was conducted. This assessment had the goal of the following two points

- Review of the data availability
- Data modifications

The goal of this is to reflect on the received data and to prepare the data for the following demand calculations. In the case of modifications that were necessary, clear descriptions and explanations were given.

Demand Scenario Development: Quantitative desk research & modelling

The key goal of the quantitative assessment was to aggregate weights for one CRM for each equipment, each technology and all technologies together.

In order to calculate the weight of CRMs contained in lower level components of one equipment, the following formula was used.

$$Weight\ of\ a\ CRM\ contained\ in\ an\ equipment\ (in\ grams) = \sum Weight_{CRM\ Component1} + Weight_{CRM\ Component\ 2} + \cdots + Weight_{CRM\ Component\ x}$$

In order to calculate the weight of a CRM across different equipment per technology, the following formula was used.

$$Weight\ of\ a\ CRM\ contained\ in\ a\ technology\ (in\ grams) = \sum Weight_{CRM\ Equipment1} + Weight_{CRM\ Equipment\ 2} + \cdots + Weight_{CRM\ Equipment\ x}$$

Lastly, in order to draw conclusions for the whole telecommunication industry, CRMs need to be aggregated across all different technologies. Thus, the following formula will be used.

$$Weight\ of\ a\ CRM\ contained\ in\ all\ technologies\ (in\ grams) = \sum Weight_{CRM\ Technology\ 1} + Weight_{CRM\ Technology\ 2} + \cdots + Weight_{CRM\ Technology\ x}$$

In order to develop the scenarios, four main aspects needed to be identified:

1) Amount of devices existing globally as of 2021
2) Future trends for each individual future technology, calculated as device developments based on expected growth rates of the rollout
3) Shares of equipment types per future technology, calculated as share of a device compared to another device
4) Material intensities per equipment type individually and for the whole technology and all technologies in grams or tons
5) Scenario timeline depending on expected rollout for the future technology

1) In order to create scenarios, firstly the amount of devices as of 2021 needed to be identified. For that, a literature research of current deployment amount of market research organizations, as well as estimations of device suppliers needed to be taken into consideration.

2) Future trends were taken through a literature research of market forecasts of market research organizations, estimations received from device suppliers or from research institutes.

In the case the retrieved information was given in percent growth rate, device amounts needed to be calculated. This was done by firstly calculating the amount of devices in 2021 and then scaling it up according to the respective time line by multiplying the growth rate. This was done through the following formula:

$$Amount\ Devices\ t(1) = Amount\ Devices\ t(0)\ \times (1 + r)^t$$

r= growth rate; t= time

In the case the retrieved information was given as amount of devices at t(0) and at t(1), a Compound Annual Growth Rate (CAGR) was calculated based on the numbers retrieved from different years and then scaled up. The formula for the CAGR is the following:

$$CAGR_{device\ development\ t(0)-t(1)} = (\frac{Value\ t(1)}{Value\ t(0)})^{\frac{1}{(t(1)-t(0))}} - 1$$

$$Amount\ Devices\ t(0 + t) = Amount\ Devices\ t(0)\ \times (1 + CAGR)$$

In the case that the amount of devices were just given by the experts, they were taken without further modifications.

3) As part of this study it needed to be defined which share of the future technologies, specific equipment types have. This needed to be defined as how much of one device comes to an amount of other devices. In order to define that, technology experts were consulted again.

4) Numbers for the material intensities per equipment and per technology were taken from the before Quantitative Assessment.

5) Scenario timelines needed to be defined after the expected rollout of the technologies. Again, experts were consulted, as well as depending on growth forecasts of market research organizations, device suppliers and research institutes, timelines were adjusted.

After having gathered the above data, three different kinds of scenarios were developed. The goal was to make it possible to compare possible demand developments related to today's levels. They included the following four types:

- A current situation: Data on how many devices are currently existing as of 2021
- A slow rollout scenario: Device development based on rather conservative forecasted growth rate until 2030 or 2050
- A fast rollout scenario: Device development based on rather positive forecasted growth rate until a 2030 or 2050
- A full rollout scenario: Hypothetical calculation of a global coverage of the future technology, without growth developments or time line

In order to forecast the demand under slow and fast rollout scenarios, the following formulas were used. The calculations were the same, solely parameters for the amount of devices vary for the different scenario types. All three calculation needed to be done for every single scenario.

$$Demand\ of\ a\ CRM\ contained\ in\ a\ device\ (t) = \sum Weight_{CRM\ Component1} \times Device\ amount_{Technology1}\ (t)\ + Weight_{CRM\ Component2} \times Device\ amount_{Technology1}\ (t)\ + \dots + Weight_{CRM\ Component\ x} \times Device\ amount_{Technology1}\ (t)$$

$$Demand\ of\ a\ CRM\ contained\ in\ a\ technology\ (t) = \sum Weight_{CRM\ Device1} \times Device\ amount_{Technology1}\ (t) + Weight_{CRM\ Device2} \times Device\ amount_{Technology1}\ (t) + \dots + Weight_{CRM\ Device\ x} \times Device\ amount_{Technology1}\ (t)$$

$$Demand\ of\ a\ CRM\ contained\ in\ future\ technologies\ (t) = \sum Demand\ CRM_{Technology1}(t) + Demand\ CRM_{Technology\ 2}(t) + \dots + Demand\ CRM_{Technology\ X}(t)$$

$$Demand\ for\ CRMs\ contained\ in\ future\ technologies\ (t) = \sum Demand\ CRM1 + Demand\ CRM2 + \dots + Demand\ CRM\ X$$

For those calculations, it is important to mention, that the time lines chosen are represented through years. No distinction between exemplarily quarter demands were made. In case demand was given in quarters of different years, the demand of one quarter was multiplied by four in order to draw conclusions on the whole year. In the case of a 2030 timeline, single years, such as 2021, 2022, 2023 were used for the forecasting. In the case of a 2050 timeline, demand was estimated as arising in a five year timeline, such as 2021, 2025, 2030, 2035.

In the case of the full rollout scenario, no demand development was pictured. Instead, hypothetical calculations were made, based on the assumption that the respective technologies would be fully rolled out worldwide. Full global rollout varied across the different technologies. Taking growth rates for the full rollout scenarios would be meaningless, since the sole goal of this calculation is to make an assumption on the total amount of material resources the technology would require.

Lastly, the calculation of the current situation depends on data gathered through literature research or experts consultations. There can be individual approaches on estimating the amount of currently used device amounts. In case they were given from experts, those device amounts were taken as a starting point. In the case device amounts needed to be calculated, the calculation methodology depended on the findings. In the subsections, clear descriptions on the calculations will be given.

Demand Scenario Assessment: Quantitative Data Analysis

After having calculated CRM amounts in 2030/ 2050 or under the full rollout scenario, results needed to be presented in a meaningful way. For the presentation of the results, the International Energy Agency (IEA) (2021) report about *The Role of Critical Minerals in Clean Energy Transition* was taken as an orientation point. For the presentation, solely CRM demand of the year 2030 or 2050 was taken. The demand development was neglected. Units are given in t, Mt or x-fold increase. The following result representations, after IEA (2021) was chosen:

- Individual future technology level: CRM demand for single technologies in 2021 compared to slow and fast rollout scenarios in 2030/ 2050 and a full rollout scenario for the largest five CRMs in weight (t/ Mt)
- Comparison between future technologies level: Aggregated CRM demand for individual technologies compared in 2021 under slow and fast rollout scenarios in 2030/ 2050 and a full rollout scenario
- Aggregated future technologies level: Aggregated CRM demand for all future technologies in 2021 compared to slow and fast rollout scenarios in 2030/ 2050 and under a full rollout scenario
- Individual CRM level: Demand for individual CRMs aggregated across future technologies in 2021 compared to slow and fast rollout scenarios in 2030/ 2050 and under a full rollout scenario

Annual World Production Rates: Quantitative Desk Research

The first step of the demand and supply comparison was to identify Annual World Production Rates for the before identified CRMs of phase one. Most of the data was taken from USGS (2020). In case no data could be retrieved from there, other sources were excepted as well. Thus, the method used was a quantitative desk research. The results should be given in tons per year. The last reported year was taken.

Demand and Supply Comparison: Quantitative Data Analysis

The goal was to put the demand for CRMs in comparison to current supply. Thus, the following calculation was conducted based on every single individual occurring CRM.

$$CRM\ Demand\ Supply\ Relation = \frac{Future\ demand\ for\ a\ CRM}{Current\ annual\ world\ production}$$

The result can either be that demand is exceeding supply x-fold or that a percentage of the supply is required to meet the demand. This calculation is done firstly on an individual technology level and secondly on all technologies aggregated. Aggregated demand will give indications on the whole telecommunication industry.

3.3. Supply Chain Resilience Strategies

Below explanations include detailed descriptions Phase 3 as shown in the above Figure 3.1.

In order to identify supply chain resilience strategies, a literature review was conducted. Focus was solely put on literature that focused on resilience in combination with "Critical Raw Materials" or "Material Criticality". Different strategies and drawbacks on the strategies from the papers were summarized and based on that recommendations on how telecommunication companies can support those strategies were given. Additionally, this study had the ambition to clearly include solely circular economy and supply chain resilience strategies. It was not the goal to put emphasis on solely corporate strategies.

Chapter 4: Critical Raw Materials in Future Technologies

Chapter 4 deals with answering the first research question: *Which Critical Raw Materials are contained in the equipment of future technologies of the telecommunications industry?.*

4.1. The Network of the Future

New trends and technologies shape the future network architecture of telecommunication providers. KPN regularly publishes the KPN Technology Book presenting relevant technology trends. It is KPN's ambition to have a heads up on identifying and monitoring trends as early as possible (KPN, 2020). The following Figure 4.1 represents the main technologies KPN has on its radar.

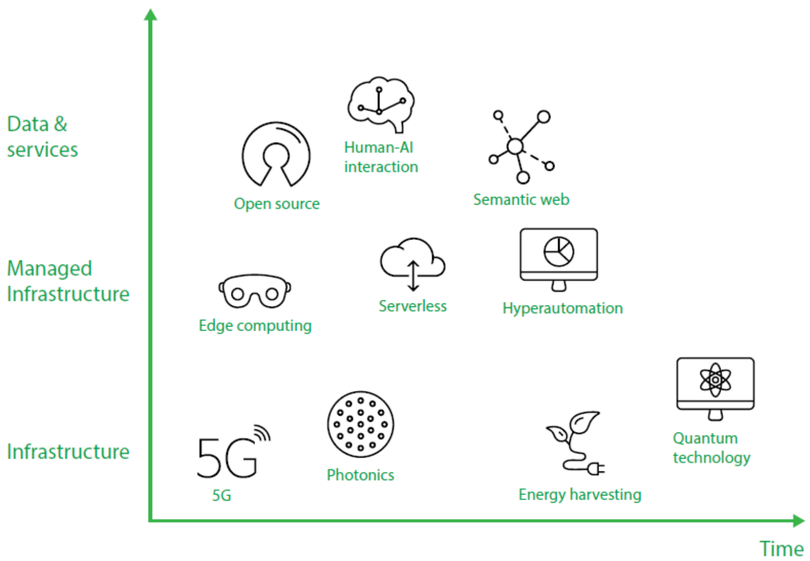


Figure 4.1: Technology Trends according to KPN (2020).

Since the goal of this study is to identify material impacts, focus technologies are part of the infrastructure and managed infrastructure technologies. From the infrastructure related technologies, this study will focus on 5G, Photonics and Quantum Technologies. Edge Computing was taken as a fourth technology, since the implementation date is the most recent.

These four technologies have a significant influence on the network of the future. How the network of the future looks likes and where the technologies can be found is represented in Figure 4.2 below.

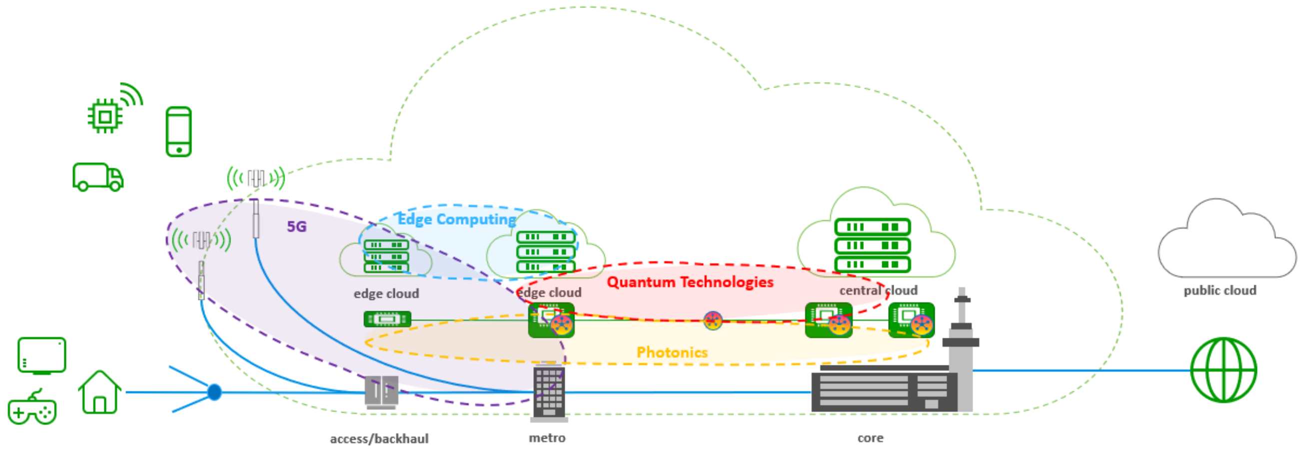


Figure 4.2: The Network of the Future including the four technologies.

5G mostly applies in the access/ backhaul network, the antennas and the metro locations. Photonics is part of the optical layer and is situated in the access/ backhaul, metro and core network. Edge Computing is more software based and is located at the edge cloud. Quantum Technologies are impacting along the metro and core locations as well.

4.2. 5G Technology

5G stands for the fifth generation of wireless network and has the benefits of larger bandwidths, higher data rates, spatial processing, beam division and forming technologies (Wani et al., 2018; Nigam et al., 2020; Juneja et al., 2021). Specifically, these include the following (Precious Metals Commodity Management; 2020):

(1) Small Cell Networks: A big number of mini base stations makes it possible for 5G to go around physical obstacles
(2) Massive MIMO: Increased cellular traffic can be handled with a much higher network capacity
(3) Beamforming: Since cellular traffic goes in very different directions, data transmission into specific directions without interference is done through beamforming
(4) Full Duplex: A new signaling method makes it possible to reroute signals with common frequencies and deliver higher data volumes as well as better efficiencies in time handling

5G has the potential of making a sustainable impact. Exemplarily, use cases include enabling the management of smart energy, reducing the need for business travels or office space by making a fast communication possible, supporting intelligent and automated supply chain movements or providing real-time information to vehicles and thus optimizing their driving (Huawei, 2020). Additionally, also smart agriculture through remote sensing leading to a reduction of water or fertilizer is a potential use case (Supplier B for 5G Technologies, 2021).

4.2.1. 5G Technology – Equipment

Typically, a 5G Mobile site includes the following equipment (Personal Communication KPN, 2020):

(1) Beamforming antennas
(2) Remote Radio Unit (RRU)
(3) Base stations

(4) Site Support Cabinet
(5) Battery Backup

Those equipment is part of the 5G Mobile Network, which in turn is part of the Radio Access Network (RAN) (Supplier B for 5G Technologies, 2021). Basically, the RAN is the layer of different base stations, which makes it possible that the telecom network can interact with devices such as mobile phones (Supplier B for 5G Technologies, 2021). The 5G Mobile Network is the layer above that, enabling that the base stations can communicate to each other and other actions can be exerted, such as network management (Supplier B for 5G Technologies, 2021). The RAN is a part of the 5G Mobile Network, including the RRU and the antennas (Supplier B for 5G Technologies, 2021). Interview or e-mail communication summaries cannot be shared due to data sharing constraints. Thus, no appendix is available for 5G Technologies.

4.2.2. 5G Technology – Critical Raw Materials

In order to identify CRMs contained in 5G equipment, interviews and e-mail communication was conducted with Expert A of a sustainable network initiative and two suppliers for 5G Technologies. Below Table 4.1 summarizes that.

Table 4.1: Overview on interviews conducted with 5G experts as part of this study.

Interviews and e-mail communication with experts	Date
Expert A from a sustainable network initiative	12.03.21; 15.03.11
Supplier A of 5G Technologies	18.12.20; 06.01.21; 20.01.21; 22.03.21; 23.04.21
Supplier B of 5G Technologies	10.11.20; 04.02.21; 01.03.21; 17.03.21; 18.03.21; 13.04.21; 15.04.21

As part of these discussions, general data on the RAN and Mobile Network, as well as specific data for the RRU and the antenna could be gathered: The first data includes CRM contents of anonymized equipment of the RAN, however with the 2017 EU list of CRMs. This means, that no lower level components could be identified. Furthermore, solely PGMs and REEs were given and thus it was not possible to identify which specific materials are contained. Due to that, all were included. Secondly, for the equipment of the Mobile Network, data represents the last 5 years of equipment used by the supplier. It was estimated that 5G equipment falls approximately into this time frame. Again, no lower level components could be identified. Thirdly, specific data for the RRU and the antenna could be gathered, however also here without lower level components. The raw data for the individual components can be found in Appendix A1. The below Figure 4.3 shows which CRMs are contained in which 5G Technology devices or network part.

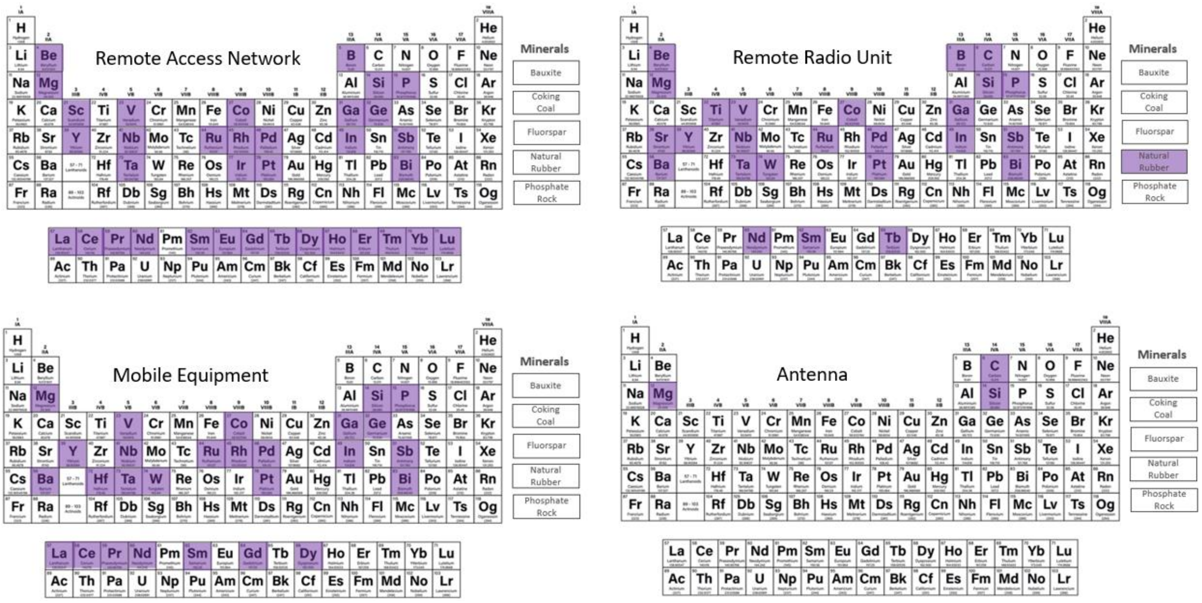


Figure 4.3: Critical Raw Materials contained in a 5G Equipment.

Figure 4.4 presents all CRMs aggregated across all different 5G Technology devices.

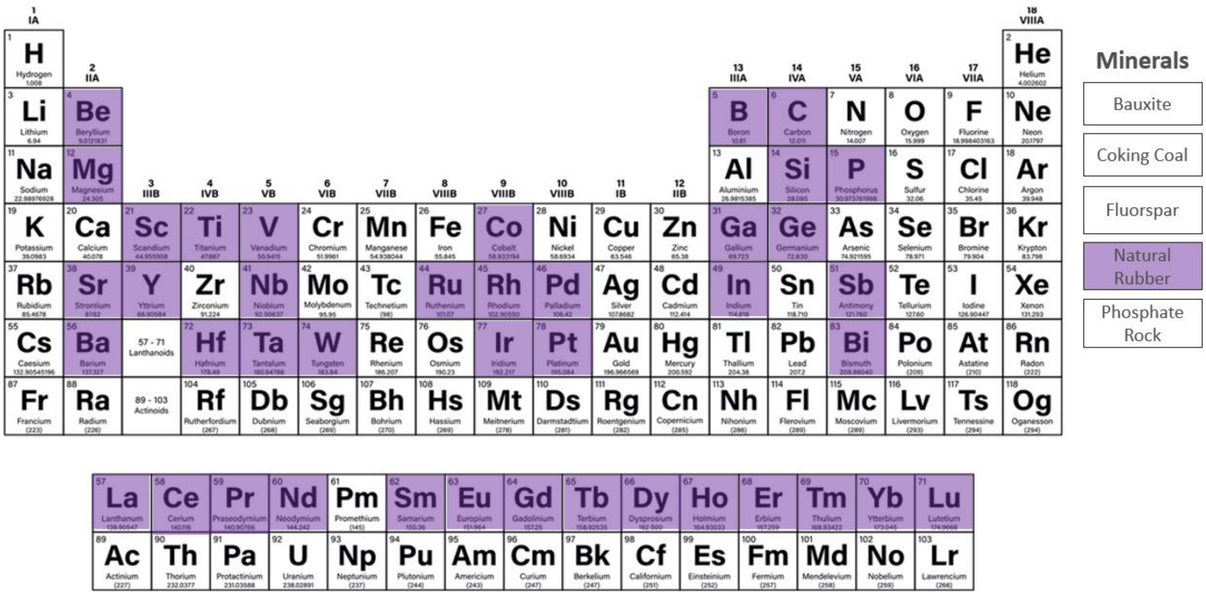


Figure 4.4: Critical Raw Materials contained in 5G Technologies.

4.2.3. 5G Technology – Supply Risk & Occurrence Assessment

Due to the fact that it was not possible to analyze which CRM is contained in which specific equipment of the RAN and Mobile Network, as part of the occurrence analysis, it was decided to just count the RAN and Mobile Network as each one part. This means that if the CRM is contained in any of the anonymized equipment, it is counted as one. Thus, the frequency of occurring CRMs ranges from 1 – 4 for 5G technologies. This might be biased by a double counting of the CRM however, since the RRU and Antenna are also part of the Mobile Equipment. The raw data of the following assessment can be found in Appendix A2. Below Figure 4.5 represents the result of the assessment.

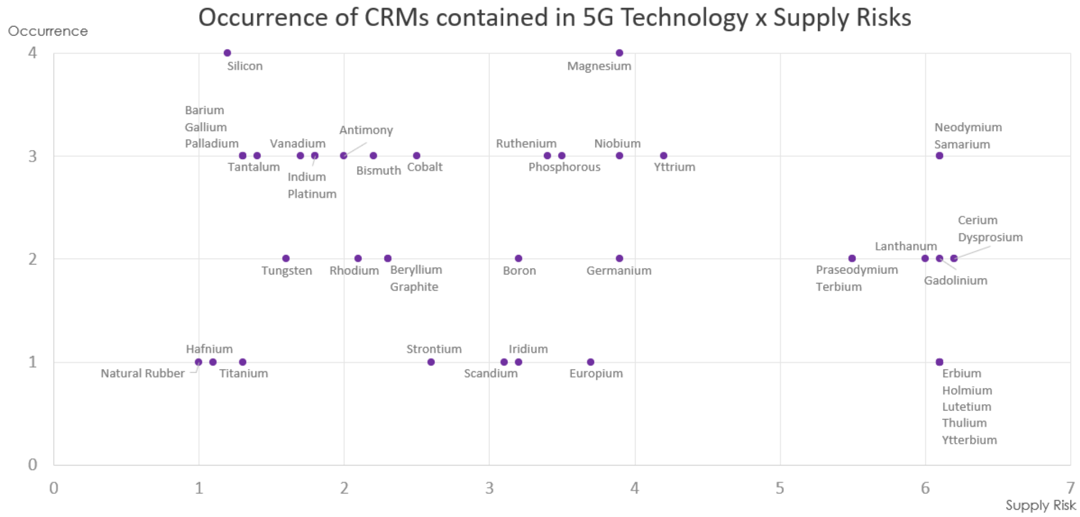


Figure 4.5: Criticality Matrix of Occurrence of CRMs contained in 5G Technology x Supply Risks.

When looking at all the gathered data for 5G Technologies, it can be found that the CRMs Si and Mg do have the highest occurrence in all four equipment. They are contained in the RRU and the antenna, and also in an anonymized device of the RAN and 5G Mobile Network. However, there are also a variety of CRMs that are contained in at least three equipment types of the data.

When looking at the supply risks of the CRMs, the overall highest occurrence and also highest supply risks are Nd and Sm. Furthermore, high supply risks and occurrence in two of four parts can be identified for Ce, Dy, Gd, La, Pr and Tb. Lastly high supply risks and occurrence in one of the 5G parts include the CRMs Er, Ho, Lutetium, Tm and Yb. The remaining CRMs are associated with rather low to medium supply risks across all occurrences.

4.3. Photonics

In the case of telecommunications, Photonics enables that photons are generated, detected and manipulated through different actions such as the transmission, signal processing, modulating and switching as well as the amplification (Amiri et al., 2018). In the network, Photonics find use through the connection of households with glass fiber cables, enables the transport of data in data centers and is used for wireless communication (KPN, 2020). Advantages of this are higher data throughput rates and speeds, lower latencies, increased bandwidths and generally more efficient networks (KPN, 2020). In general, as electrons revolutionized telecommunications in 20th century, the same is happening with Photonics in the 21st century (Amiri et al., 2018).

Photonics can be an enabler for sustainable use cases. Among those cases are improvements in health care through high-quality video transmission for operations assisted by robots, the reduction of energy in data centers through the implementation of Photonic chips or improved optical measurements of water or air qualities (National Agenda Photonics, 2018).

4.3.1. Photonics – Equipment

Photonics components interact in photonics networks and do reach from central core locations to antennas located at base stations (Amiri et al., 2018). Those components can include the following (Photonics21, 2017):

(1) Multiplexers
(2) Optical Switches
(3) Amplifiers
(4) Transceivers
(5) Lasers
(6) LEDs
(7) Detectors
(8) Splitters
(9) Connectors
(10) Passive optical components
(11) Optical Fiber Cables
(12) PICs (Zhao et al., 2019)

The selected devices representing Photonics include Photonic Transceivers, Photonic Amplifiers and Photonic Optical Switches. The below Table 4.2 gives an overview on the lower level components of the devices.

Table 4.2: Overview on the lower level components of Photonics devices currently in use.

Photonic Device	Lower Level Component
Photonic Transceiver	Photonic Integrated Circuits (PIC)
	Packaging
	Fiber
	Connector Lanes
	Wires
	Ceramics
	Epoxy
	Heatsinks
	Solders
	Additional parts
Photonic Amplifier	General components
	Additional components
	Electronics
Photonic Optical Switch	General components
	Modulator
	Lenses
	Optical Fiber
	Research components

In order to identify raw material contents of future equipment, interviews were conducted with research institutes as well as photonic device manufacturers. Table 4.3 gives an overview on the interviews. Interview and e-mail communication summaries can be found in Appendix B1. Raw material data can be found in Appendix B2.

Table 4.3: Overview on interviews conducted with Photonics experts as part of this study.

Interviews and e-mail communication with research institutes	Date
Professor A for Photonics Integration	14.12.2020; 15.12.2021; 12.01.2021; 11.03.2021
Professor B for High Capacity Optical Transmission	19.03.2021
Professor C for Electro-Optical Communication Systems	24.03.2021
Interviews and e-mail communication with photonic device manufacturers	
Supplier A for Photonic Devices	12.01.2021; 26.02.2021; 09.03.2021
Supplier B for Photonic Devices	05.02.2021
Supplier C for Photonic Devices	02.04.2021

4.3.2. Photonics – Critical Raw Materials

The below Figures 4.6 represent the CRMs contained in the various Photonic devices.

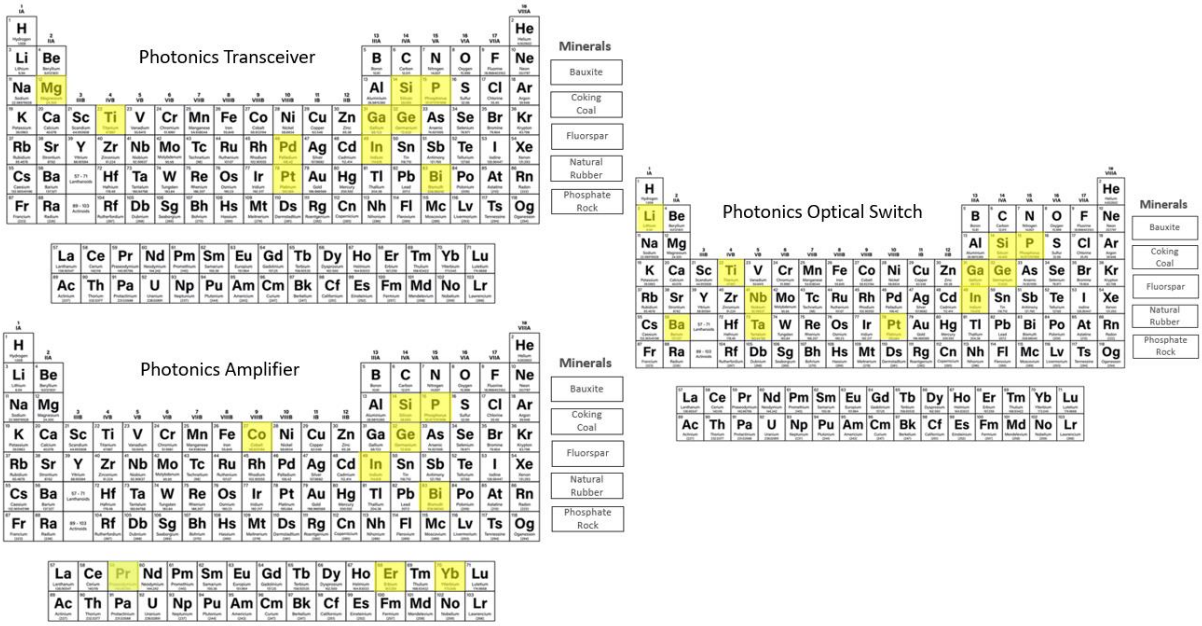


Figure 4.6: Critical Raw Materials contained in a Photonics Devices.

The below Figure 4.7 shows the table of elements and all contained CRMs aggregated from the different selected Photonics devices.

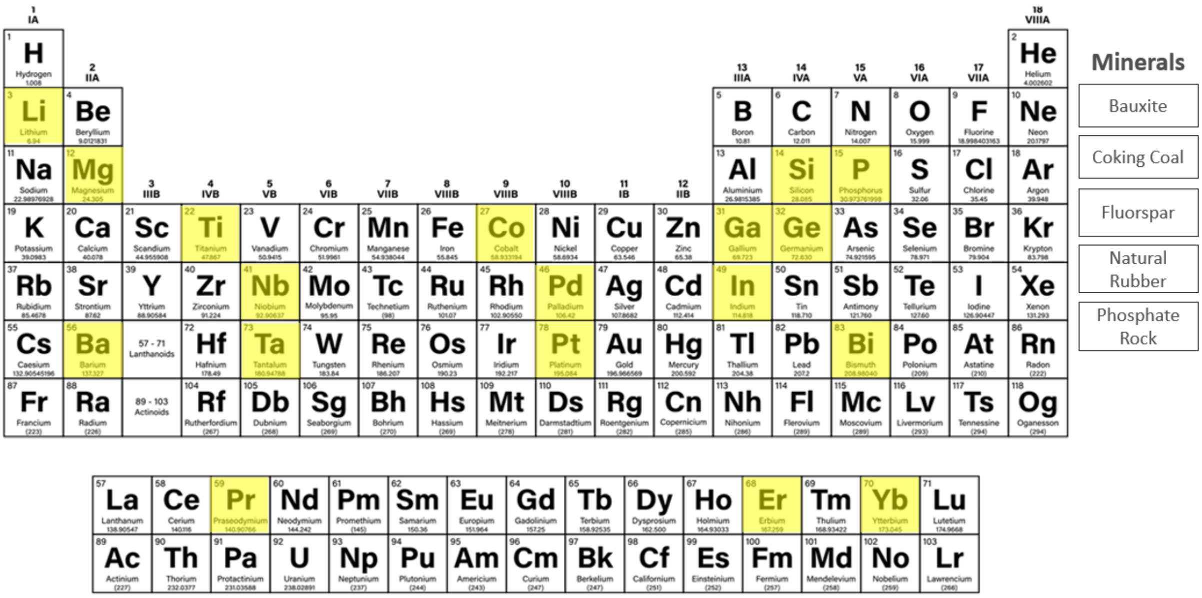


Figure 4.7: Critical Raw Materials contained in Photonics.

4.3.3. Photonics – Supply Risk & Occurrence Assessment

The result of the Supply Risk & Occurrence Assessment can be found in the below Figure 4.8. The raw data as well as the assessment for the different Photonics Devices can be found in Appendix B3.

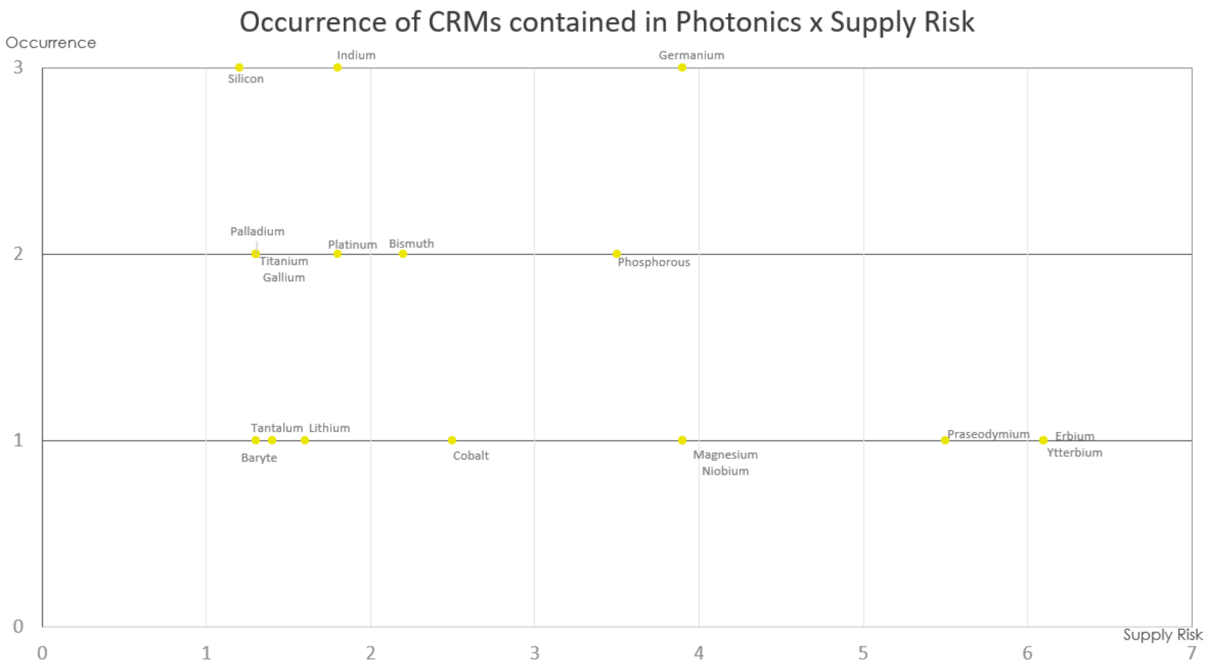


Figure 4.8: Criticality Matrix of Occurrence of CRMs contained in Photonics x Supply Risks.

When looking at the occurrence of CRMs contained in Photonics equipment, Si, In and Ge occur in all three equipment. Moreover, in at least two of the three equipment, the CRMs Pd, Ti, Ga, Pt, Bi and P would be identified. No CRMs could be identified that are of high occurrence as well as of high supply risk. However, the CRMs Pr, Er and Y, that are occurring in one equipment (Photonics Amplifier), are associated with very high supply risks. The remaining CRMs are of rather low to medium supply risks.

4.4. Edge Computing

With the increasing data processing and storing needs deriving from innovations such as IOT or 5G, cloud computing is no longer an option (Sunyaev, 2020; Madsen et al., 2013; Brogi et al., 2017). Thus, the computing of this data needs to be done closer to where the data is generated with lower latencies, at the so-called *Edge* (Sunyaev, 2020; Bittencourt et al., 2015). Edge Computing represents the connections between the cloud and different devices that are capable of processing and reacting to data (Sunyaev, 2020).

Edge Computing means firstly that core functions such as computing, controlling, decision making, storage or communicating are moved close to the devices that depend on the functions and secondly those devices can be integrated to serve those functions, exemplarily through intelligent sensors (Sunyaev, 2020). This specifically means that the network architecture of Edge Computing even makes it possible to distribute those core functions where needed (Sunyaev, 2020). Several technologies are part of Edge Computing, among which are sensor networks, ad hoc networking, mobile data capture or peer-to-peer (Sunyaev, 2020).

Sustainable advantages of this are that with lower latencies, structural changes in key sectors such as smart energy, automated driving or mobile health, can be enabled, which will contribute to decarbonization (European Commission, 2020c. Use cases include exemplarily that data needs to be processed in real-time for autonomous driving vehicles (Bonomi et al., 2012), leading to improved security, reliability and safety (European Commission, 2020c). Another example are smartphones connected to sensors placed on a human's body monitoring heart rates (Sunyaev, 2020).

4.4.1. Edge Computing – Equipment

The identification of core Edge Computing equipment was done together with Edge Computing Supplier A (2021). The information gained included the following three equipment:

(1) Edge Computing Server
(2) Small Switch
(3) Integrated Accelerator Unit (GPU)

As part of this research, solely data on the Edge Computing Server could be gathered. This data was collected uniquely from Edge Computing Supplier A (2021). No additional interviews with research institutes were conducted. The following Table 4.4 gives an overview of the lower level components of an Edge Computing Server.

Table 4.4: Overview on the lower level components of Edge Computing (Interview with Edge Computing Supplier A (2020).

Edge Computing Device	Lower Lovel Components
Edge Computing Server	Motherboard
	Smart Storage Battery
	Fiber Optical Cable
	Small Form Factor Hard Drive
	Large Form Factor Hard Drive
	High Speed Hard Drive

Data on raw material contents were analyzed after Edge Computing Supplier A provided an excel file with detailed information on the Edge Computing Server. It needs to be mentioned that solely one hard drive of the above three mentioned are contained in an Edge Computing Server. However, since mapping technological routes was outside the scope of this research, all CRMs contained were included. Interview or e-mail communication summaries cannot be shared due to data sharing constraints, however raw material data can be found in Appendix C1.

4.4.2. Edge Computing – Critical Raw Material

The below Figure 4.9 represent the CRMs contained in an Edge Computing Server.

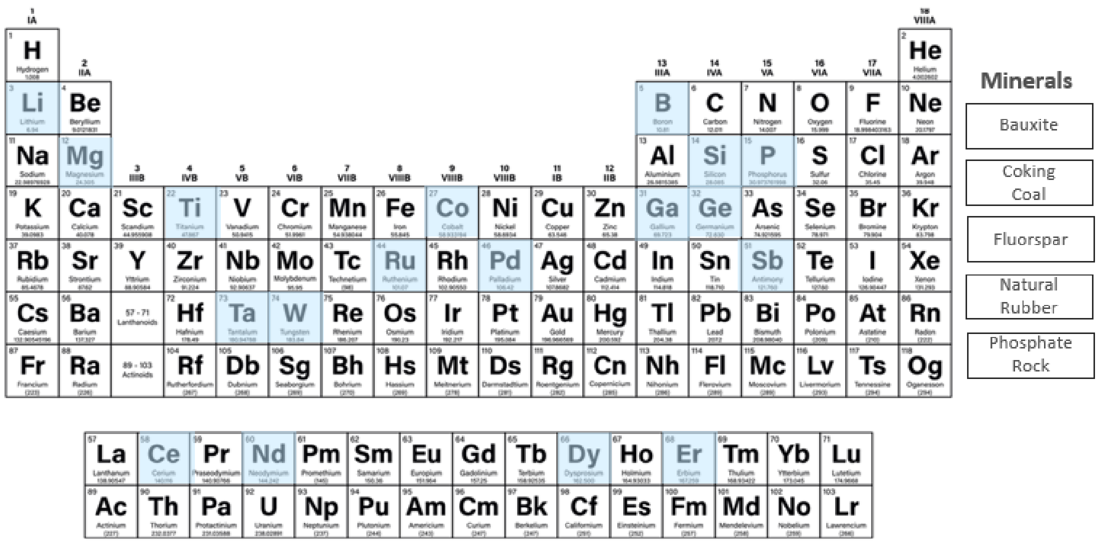


Figure 4.9: Critical Raw Materials contained in an Edge Computing Server.

4.4.3. Edge Computing – Supply Risk & Occurrence Assessment

The result of the Supply Risk & Occurrence Assessment can be found in below Figure 4.10. Additionally, the raw data of the assessment can be found in Appendix C2.

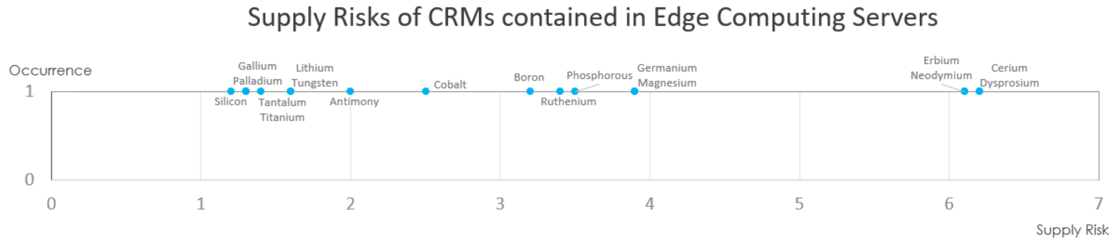


Figure 4.10: Criticality Matrix of Occurrence of CRMS contained in Edge Computing Servers x Supply Risks.

Looking at the supply risks of CRMs contained in an Edge Computing Server, especially the CRMs Ce, Dy, Er and Nd are of high risk for the manufacturing. Most CRMs contained are associated with medium supply risks.

4.5. Quantum Technologies

Quantum Technologies have the unique possibility of creating a fully secure communication (Appas et al., 2021). Amongst those technologies it can be distinguished between Quantum Communication, Quantum Computing and Quantum Internet (Internal Expert KPN Quantum Communication, 2020). As part of this case study, solely focus was put on Quantum Communication.

In the case of Quantum Communication, the vision is to create a network that can be used by everyone for every application, whether classical telecommunication applications or quantum applications (Razavi, 2018). This network should enable connectivity with strong security aspects based on physical laws (Joshi et al., 2020). The key underlying quantum applications is quantum key distribution (QKD), which creates secret keys between different parties communication with each other and achieve unconditional security (Dianati et al., 2008).

Quantum networks underly some criteria according to Razavi (2018): Quantum applications solve security concerns of operators, however have to be designed in a cost-efficient way to prove profitable. Thus, it is aimed at using the already existing network infrastructure of fiber-optical communications (Razavi, 2018). Another criteria is that quantum networks should be multiplexed and thus be usable from several users (Razavi, 2018). Lastly, building trust in the network is crucial for exchanging data (Razavi, 2018), since security concerns can hinder telecommunications.

Use cases include the protection of connected devices for IOT from cyber-attacks and algorithm-based quantum computer hacks through the processing of enough quantum bits, potentially affecting millions of devices (Richdale, 2017). Letting exemplarily smart cities or autonomous driving cars being exposed to vector attacks, can even harm national security (Richdale, 2017). Thus, Quantum Devices in telecommunication are exceptionally crucial for our security and privacy.

4.5.1. Quantum Technologies – Equipment

The Quantum Communication equipment was defined together with Expert A on Quantum Communication and Quantum Internet. All interview transcripts can be found in Appendix D1.

According to the interview with Expert A of Quantum Communication (2020), there are three Quantum devices that are currently used: Quantum Routers, Quantum Senders and Quantum Receivers. The lower level components of each of those devices is represented in Table 4.5. Solely hardware related components are represented.

Table 4.5: Overview on the lower level components of quantum devices currently in use (Interview Expert A for Quantum Communication, 2020).

Quantum Device	Lower Level Components
Quantum Router	Integrated Photonics
	MEMS Switches
	Electronics
	Metal Box
Quantum Sender	Lasers
	Integrated Photonics
	Modulator
	Quantum Dots
	Cryogenics
	Electronics
	Metal Box
Quantum Receiver	Modulator
	Quantum Detector
	Superconducting Detector
	Cryogenics
	Integrated Photonics
	Electronics
	Metal Box

Furthermore, there are two additional quantum devices, Quantum Memories and Quantum Receivers, that are still in the research phase and will be earliest on the market between 2025 and 2030 (Interview Expert A on Quantum Communication, 2020). Since it was too complex to draw conclusions on the technological routes, these two devices were excluded from this study.

In order to identify raw material contents of lower level components, a total amount of eleven interviews were conducted with internal Quantum Communication experts at KPN, research institutes and quantum device and component manufacturers. Additionally, in three cases communication was only done over email. The following Table 4.6 gives an overview on where information was retrieved. Additionally, raw materials contained in Quantum Devices can be found in Appendix D2.

Table 4.6: Overview on interviews conducted with Quantum Communication experts as part of this study.

Interviews and e-mail communication with research institutes	Date
Expert A for Quantum Communication	28.10.20; 11.11.20; 27.11.20; 18.01.21; 25.03.21
Expert B for Quantum Technologies	10.02.2021
Expert C for Photonic Quantum Technologies	19.02.2021
Professor A for Semiconductor and Solid State Physics	18.02.2021
Professor B for High Capacity Optical Transmission	19.03.2021
Professor C for Cryogenics	02.03.2021; 03.02.2021
Interviews and e-mail communication with quantum device manufacturers	
Manufacturer A for quantum devices	12.02.2021
Manufacturer B for quantum devices	15.03.2021

4.5.2. Quantum Technologies – Critical Raw Materials

The below Figures 4.11 represent the CRMs contained in Quantum Communication devices. It is however crucial to mention, that electronics were excluded from the below list, since no proper data could be retrieved on what kind of PCB were used in the different devices. These would however mostly likely add additional CRMs to the list.

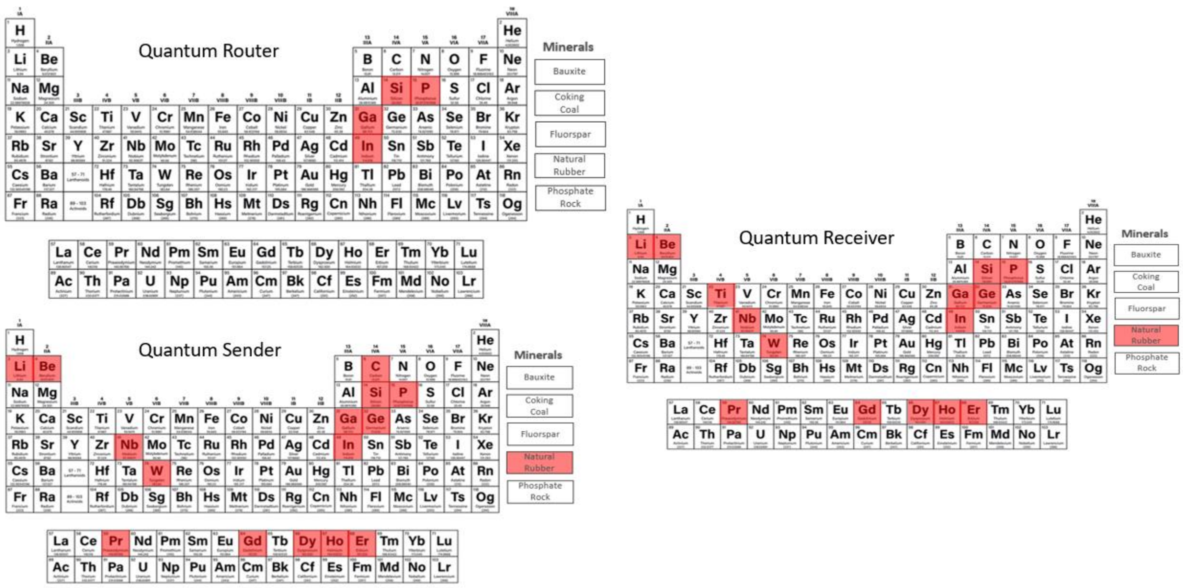


Figure 4.11: Critical Raw Materials contained in the different Quantum Devices.

The below Figure 4.12 shows the table of elements and all contained CRMs aggregated from the different selected Quantum Communication devices.

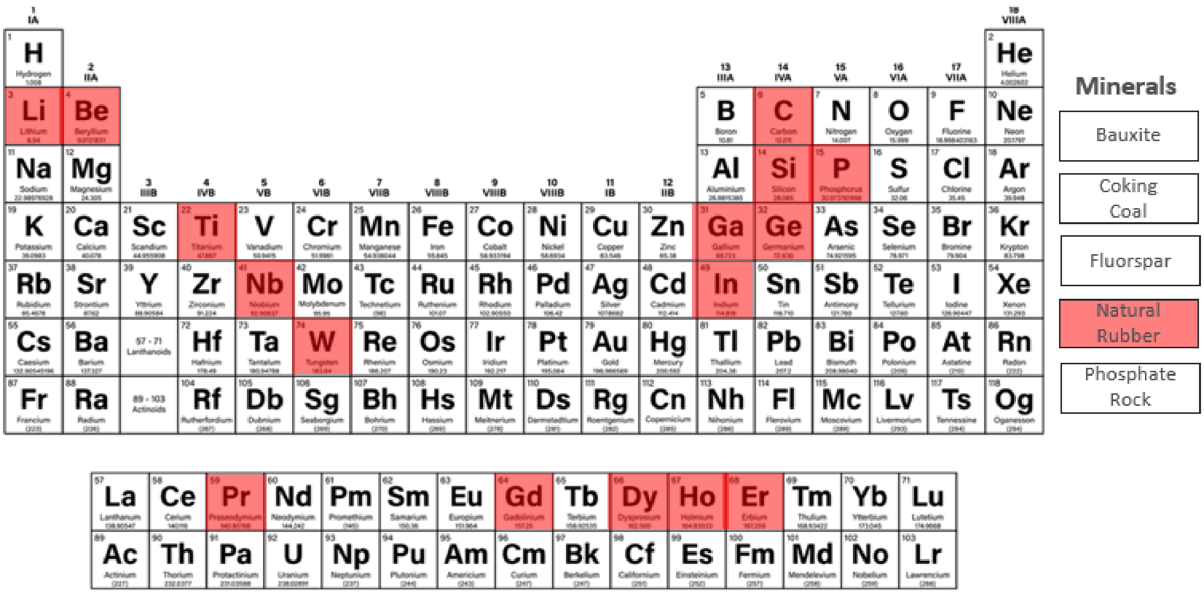


Figure 4.12: Critical Raw Materials contained in Quantum Technologies.

4.5.3. Quantum Technologies – Supply Risk & Occurrence Assessment

The result of the Supply Risk & Occurrence Assessment can be found in below Figure 4.13. Additionally, the raw data of the assessment can be found in Appendix D3.

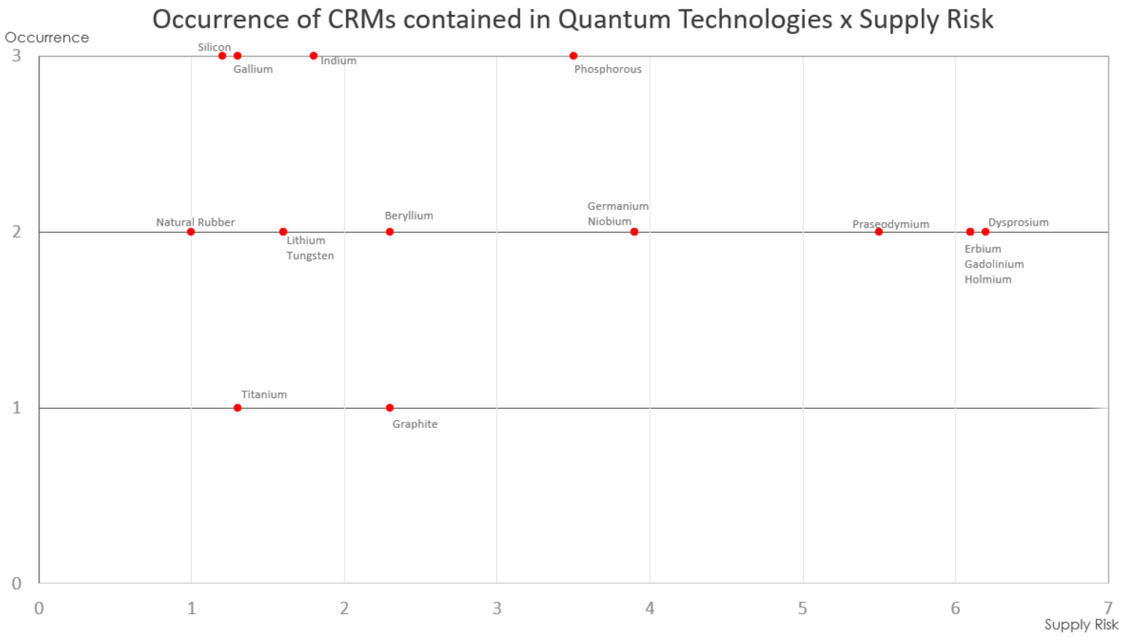


Figure 4.13: Criticality Matrix of Occurrence of CRMs contained in Quantum Technologies x Supply Risks.

When looking at the occurrence of CRMs within the quantum equipment and the supply risks, the elements Ga, In, Si and P occur in every single device. Most other CRMs are contained in at least two of three Quantum Devices. Looking at the supply risks, highest risks could be identified for Dy, Er, Gd, Ho and P, all contained in two devices.

4.6. CRMs in Future Telecommunication Technologies Equipment

In order to draw conclusions for the future of the whole telecommunication industry, the occurrence analysis was conducted based on CRMs occurring in the four different technologies. The below Figure 4.14 is a visual representation on the CRMs contained in the different future technologies.

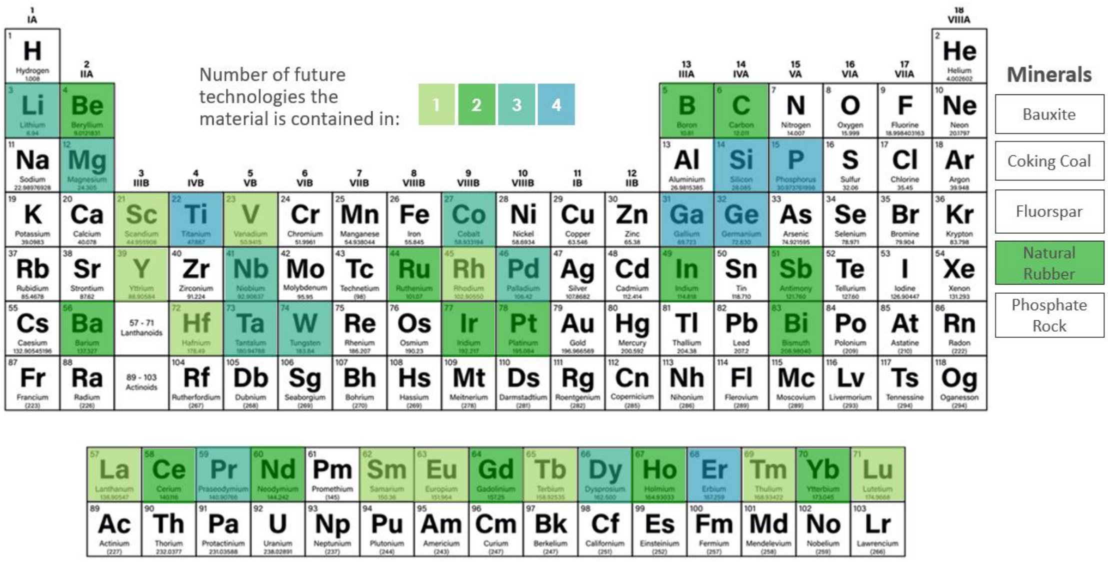


Figure 4.14: Overview on all CRMs contained in all future technologies including their occurrence.

Again, a very broad variety of different CRMs could be identified for the future technologies. When comparing the different technologies, most of the CRMs are contained in 5G Technologies, followed by Photonics, Edge Computing and lastly Quantum Technologies. In below Figure 4.15, the occurrence in future equipment is mapped with the supply risks associated with the CRMs. The raw data for it can be found in <u>Appendix E1</u>.

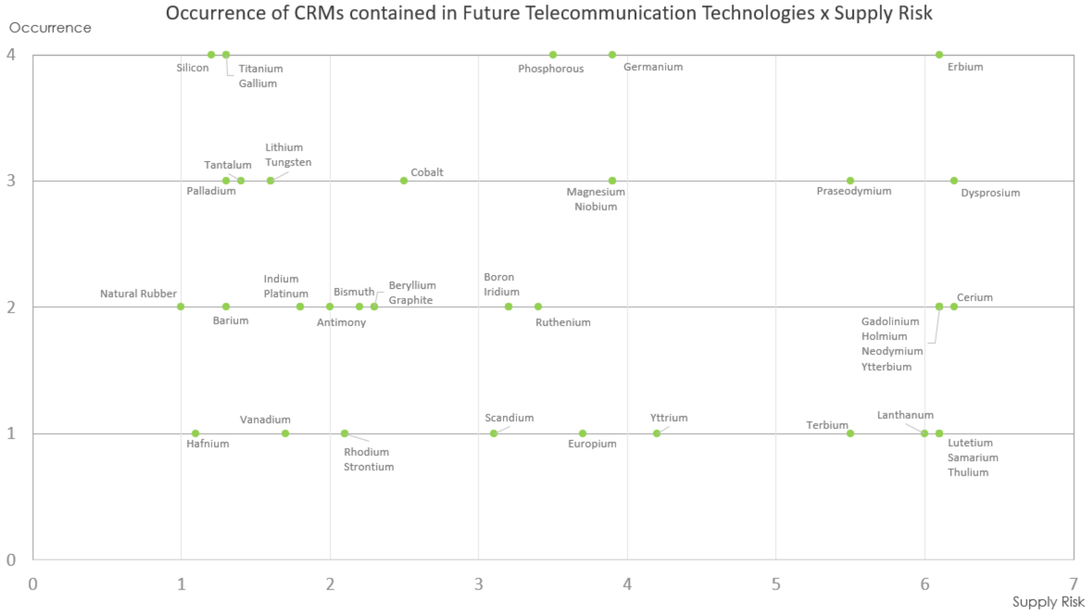


Figure 4.15: Criticality matrix of occurrence in future equipment times supply risks.

The most frequently occurring CRMs across the four technologies are Si, Ti, Ga, P, Ge and Er. Furthermore, there is a range of CRMs included in three out of the four technologies, which are Pd, Ta, Li, W, Co, Mg, Nb, Pr and Dy. Looking at the highest occurrence, as well as highest supply risks, Er clearly stands out. However, also Pr and Dy are associated with very high supply risks, while also having a high occurrence. Additionally, a variety of different CRMs might only occur in one or two technologies out of four, however do still have a high supply risks, including Ce, Gd, Ho, Nd, Yb, La, Lu, Sm, Tm and Tb.

Chapter 5: Critical Raw Material Demand Scenarios

The following chapter deals with the second research question *How does the demand develop for Critical Raw Materials contained in future technologies of the telecommunications industry until 2030 and 2050?.*

5.1. Assessment of Critical Raw Materials Weight Data

The pre-assessment includes two parts: The assessment on the data availability and the required modifications of the data to create the demand scenarios.

CRM Weights Data Availability

The first part of the pre-assessment included a visual inspection of the available data. Due to data sharing constraints and actual data availability, CRM weights for every single selected device could not be gathered. Appendix F gives a detailed overview on which data could be collected and which is missed. For 5G technologies, solely CRM weights data on an early used Remote Radio Unit and a typical antenna could be gathered. For Photonics, the data includes weights for the Photonics Transceiver, as well as the Photonics Amplifier. For the Edge Computing Server, detailed material data could be gathered. Lastly, for Quantum Technologies, estimates of the materials weights contained in all three devices could be gathered, except for Gadolinium contained in Quantum Senders and Quantum Receivers.

CRM Weights Data Modifications

The second step of the pre-assessment contained checking on how the data is presented and identifying how it can be used for the scenario development.

Firstly, for 5G Technologies and the Edge Computing Server, weights data could solely be gathered for CRMs, while for the other technologies weights for all raw materials contained could be gathered. Due to the fact, that this research solely focuses on CRMs, all other raw materials contained in Photonics and Quantum Technologies were excluded. Additionally, CRM weights per lower level component of equipment could only be gathered for the Photonics Transceiver, the Edge Computing Server and the Quantum Devices. For the remaining equipment this was not possible.

Secondly, the received data was delivered in the unit of x milligrams or x grams of CRM contained per device for nearly all technologies. Solely in the case of the Photonics Transceiver and Amplifier, the unit varied. For the Photonics Amplifier the delivered data was as either “950 – 3000 wt-ppm” exemplarily or “6 – 8% wt%”. In order to make material calculations it was decided to take averages. In this case thus “1975 wt-ppm” and “7% wt%”. According to Supplier C for Photonics Devices (2021), a standard Photonic Amplifier weights between 0,8kg – 1kg. Again here an average of 0,9kg was assumed.

Thirdly, the reported data often included the same CRM weights for different part of the devices, exemplarily as alloys like GaAs. In order to solve this, the chosen approach was to divide weights by the amount of elements contained in the alloys. In the case that GaAs would represent a weight of 10 grams, it was estimated that out of this alloy, 5 grams can be directed to Gallium and 5 grams to Arsenide.

Fourthly, it is important to mention, that detailed weights could only be gathered for 5G Technologies, Edge Computing and Photonics. In the case of Quantum Technologies, all weights data are just based on assumptions. Exemplarily, all trace materials, such as Er, Ho or Dy were given as 0,001 grams. Since Quantum Technologies are in a very early stage of development, it was not possible to define how much of one material will really be used (Expert A for Quantum Communication, 2021).

5.2. Critical Raw Material Demand Development

There were three scenarios developed per technology. Additionally, for 5G Technologies, Photonics and Edge Computing, a time frame of 2030 was chosen, while for Quantum Technologies a later time frame of 2050 was chosen. This is due to the fact that it is not expected that Quantum Technologies will be globally deployed by 2030 already (Expert B for Quantum Communication, 2021). The following Figure 5.1 gives an overview on the key points for each of the scenarios.

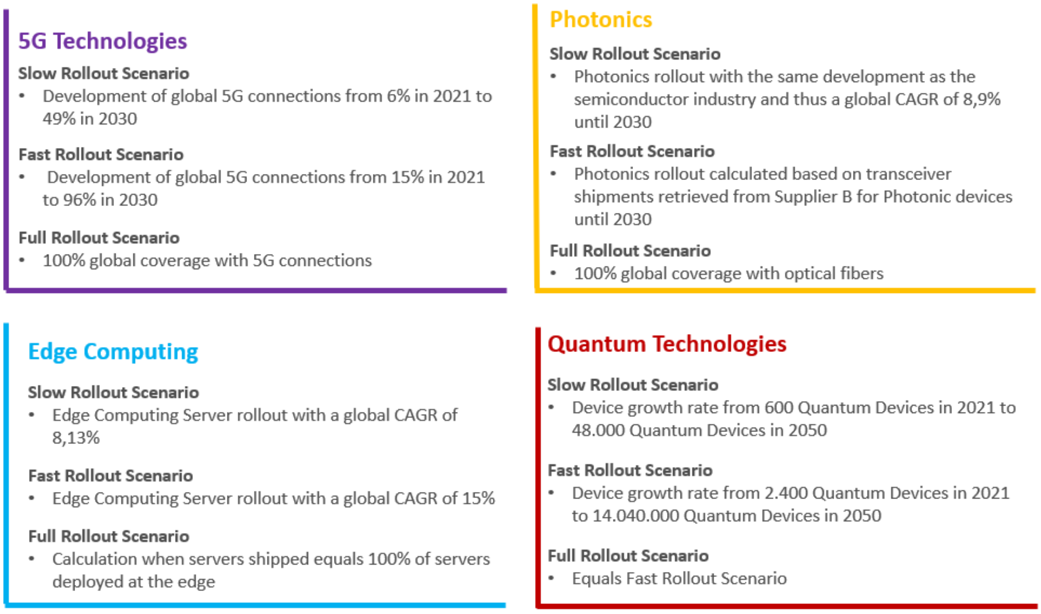


Figure 5.1: Scenarios chosen for the future telecom technologies.

5.2.1. 5G Technology – Demand Scenarios

According to discussions with 5G Technology Suppliers A and B (2021), there are generally 2 RRUs and 3 antennas at each 5G base station. Due to data constraints, it was necessary to calculate the amount of RRUs and antennas based on an average amount of base stations per square km located in global settlement areas. Then, it was calculated how much global coverage is achieved in 2021 of the global settlement area and how many RRUs and antennas would be required for that. Urban, sub-urban and rural areas distinctions would be necessary (Supplier A for 5G Technologies, 2021), however were neglected, as well as different 5G Technologies (Wisely et al., 2018).The amount of base stations also depends on the different mmW of different cells (Wisely et al., 2018). However, to make very detailed calculations on the amount of base stations, is outside the scope of this study. Thus, the goal was to take an average number that could be used for urban as well as rural areas.

Wang et al. (2020) conducted research on the amount of 5G base stations necessary for a study area. It was identified that to achieve a 5G coverage of at least 95%, at least 45 base stations per km^2 need to be employed (Wang et al., 2020). This was in line with additional research of Ge et al. (2016), estimating 45 – 50 base stations per km^2 and Palizban et al. (2017), estimating 40 – 60.

According to Florczyk et al. (2019), out of the total land and water mass on the earth, the human settlement space represents around 19.500.000km^2 of area.

Slow and fast rollout scenarios of 5G Technologies until 2030

Within their report The Mobile Economy 2020, GSMA (2020) predicts the development of global 5G connections from 2021 to 2025. The predictions is that 20% of all global connections will be covered by 5G until 2025, which is equal to around 1.8 billion 5G connections (GSMA, 2020). In 2023, around 1 billion connections are expected to be covered, equal to around 12% of all connections (GSMA, 2020). These numbers were taken for a slow rollout scenario and scaled up from 2027 until 2030, assuming the same growth rate.

Ericsson (2020) estimates that the global 5G coverage is 15% by the end of 2020. This number is taken for the calculation of 2021. Furthermore, Ericsson (2020) predicts that in 2026, the coverage will reach 60% of the global population. In order to estimate the development of base stations worldwide according to this growth rate, a constant growth between 2021 and 2026 was assumed and this was scaled up to 2030. The results of that are used for the fast rollout scenario.

The below Table 5.1 shows the device development after the two scenarios.

Table 5.1: Amount of 5G base stations, RRUs and antennas until 2030 under a slow and fast rollout scenario.

	In Billion	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Slow rollout scenario	5G Base Stations	0,06	0,09	0,12	0,16	0,2	0,24	0,29	0,35	0,41	0,48
	5G RRUs	0,12	0,18	0,24	0,32	0,4	0,48	0,58	0,70	0,82	0,96
	5G Antennas	0,18	0,27	0,36	0,48	0,60	0,72	0,87	1,05	1,23	1,44
Fast rollout scenario	5G Base Stations	0,15	0,23	0,32	0,41	0,50	0,59	0,67	0,76	0,85	0,94
	5G RRUs	0,29	0,47	0,64	0,82	1,00	1,17	1,35	1,52	1,7	1,87
	5G Antennas	0,44	0,70	0,97	1,23	1,50	1,76	2,02	2,28	2,54	2,82

The underlying calculations and RRU and antenna CRM demand developments can be found in Appendix G.

Full global rollout of 5G Technologies

In order to predict the effects on demand, in case 5G Technologies fully replaces other mobile generations on a global level, a 100% global population coverage was assumed. This resulted in the following potentially required material demand, as shown in Table 5.2. The calculations can be found in Appendix G.

Table 5.2: Required material tons under a full global rollout of the selected 5G devices.

CRMs	In tons	*CRMs*	In tons
Antimony Sb	15.995,85	Palladium Pd	824,85
Boron B	468	Platinum Pt	40,95
Barium Ba	172.190,85	Ruthenium Ru	33,15
Beryllium Be	2.250,3	Silicon Si	5.436.176,85
Bismuth Bi	10.678,2	Samarium Sm	0,59
Graphene C	12.436.741,2	Strontium Sr	34.649,55
Cobalt Co	473,85	Tantalum Ta	1.454,7
Gallium Ga	175,5	Terbium Tb	29,25
Indium In	85,8	Titanium Ti	338.551,2
Magnesium Mg	5.142.547,8	Tungsten W	27,3
Neodymium Nd	442,65	Vanadium V	0,06
Niobium Nb	0,004	Yttrium Y	26.050,05
Phosphorous P	5.224,05	Natural Rubber	23,4

Demand Comparison for the highest weight containing CRMs in 5G Technologies

The following Figure 5.2 shown comparisons of the demand for the CRM in 2021, slow and fast scenarios until 2030 and a full rollout scenario.

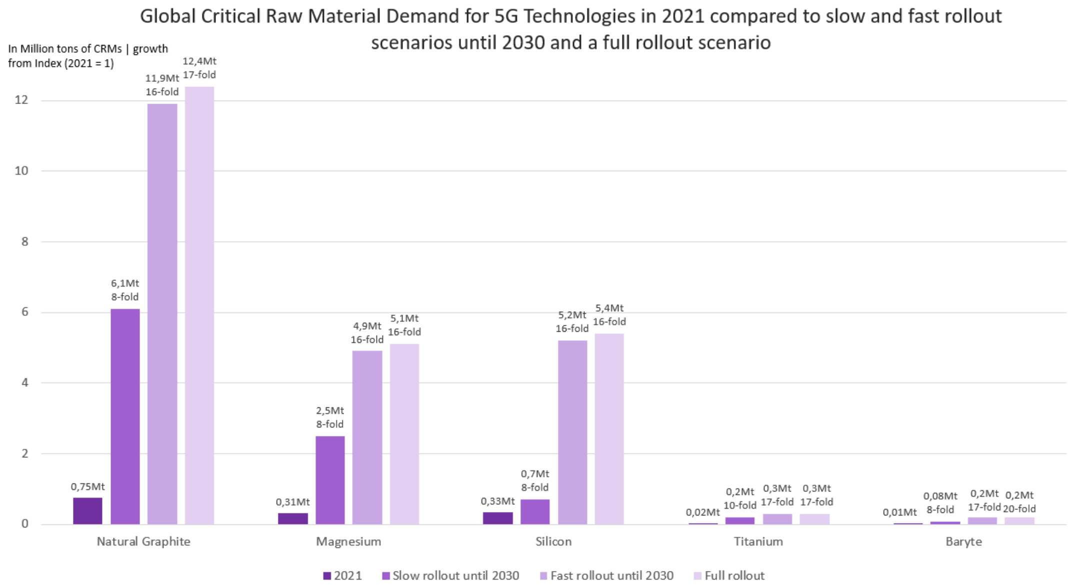


Figure 5.2: Global CRM demand for 5G Technologies in 2021 compared to slow and fast rollout scenarios until 2030 and a full rollout scenario.

The five CRMs with the biggest weights in tons contained in 5G Technologies are Natural Graphite, Mg, Si, Ti and Ba in the respective order from highest to lowest. Compared to the index of 2021, the different CRMs are growing 8 to 10-fold under the slow rollout scenario until 2030, 16 to 17-fold under the fast rollout scenario until 2030 and between 16 to 20-fold under a full rollout scenario.

5.2.2. Photonics – Demand Scenarios

As a starting base for the year 2021, numbers of Yole Développement (2020) were gathered. Yole Développement (2020) estimated that in 2020, there will be 183 million units of Photonic Transceivers worldwide, rising to 211 million units by 2025. Thus, as part of this case study it is estimated that in the year of 2021, 188,6 million Photonic Transceivers are employed. The starting base for Photonic Amplifiers in the year 2021 is 9,43 million units, due to the fact that there are 20 Photonics Transceivers coming on one Photonics Amplifier (Supplier C for Photonic Devices, 2021). The first step was to calculate the weight per Photonics device. This can be found in Appendix H1.

Slow and fast rollout scenarios of Photonics until 2030

For predicting the amount of devices for Photonic Transceivers and Photonic Amplifiers, discussions were made with Supplier C for Photonic devices. Generally, similar trends for the development of Photonics can be seen as in past for electronics (Supplier C for Photonic Devices, 2021). Semiconductors are drivers for the development of electronics (Deloitte, 2019). The major part of the revenue from the semiconductor industries comes from communication electronics, such as wireless communication (Deloitte, 2019). Thus, historic growth rates of the semiconductor industry will be taken as part of the slow rollout scenario to assume future growth rates of semiconductors and thus also Photonics devices. Between 1978 and 2018, the average CAGR of the semiconductor industry was 8,9% (Manners, 2017), which forms the basis for the slow rollout scenario.

For the fast rollout scenario, device amounts were gathered from Supplier B for Photonic devices. The data displays an estimated number of transceivers, shipped per year on basis of the global optical component market. It can be assumed that a transceiver is replaced between 5 – 10 years (mostly due to upgrades) (Supplier B for Photonics Devices, 2021). The data represents the time frame of 2016 until 2025. Thus, some calculations were made in order to scale up until 2030. These calculations can be found in Appendix H2. The result for both scenarios are the following device amounts until 2030 as shown in Table 5.3.

Table 5.3: Amount of Photonic devices until 2030 under a slow and fast rollout scenario.

Scenario	Device	Amount Device in Million [time]									
		2021	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Slow rollout scenario	Photonic Transceivers	188,6	205,39	223,67	243,57	265,25	288,86	314,56	342,56	373,05	406,25
	Photonic Amplifiers	9,43	10,27	11,18	12,18	13,26	14,44	15,73	17,13	18,65	20,31
Fast rollout scenario	Photonic Transceivers	188,6	282,4	376,2	470,0	570,2	672,48	777,83	886,34	998,1	1113,22
	Photonic Amplifiers	9,43	14,12	18,81	23,5	28,51	33,62	38,89	44,32	49,91	55,66

The CRM demand development per device can be found in Appendix H2.

Full global rollout of Photonics

In order to estimate the global rollout of Photonics, a calculation based on the global coverage of optical fiber cables was chosen. For that firstly the worldwide coverage of today was set equal to the amount of transceivers after Yole Développement (2020). Secondly, the amount was scaled up to a potential full global coverage. The exact calculations can be found in Appendix H2. The following Table 5.4 shows the results of multiplying the device amounts with the CRM weights.

Table 5.4: Required material tons under a full global rollout of the selected Photonics devices.

CRMs	In tons	CRMs	In tons
Bismuth Bi	44,56	Phosphorous P	39,2
Erbium Er	111,63	Platinum Pt	0,05
Gallium Ga	0,13	Praseodymium Pr	20,70
Germanium Ge	282,23	Silicon Si	31.078,14
Indium In	39,32	Titanium Ti	0,01
Magnesium Mg	7,9	Thulium Tm	121,67
Palladium Pd	0,01		

Demand Comparison for the highest Weight containing CRMs in Photonics

The following Figure 5.3 shown comparisons of the demand for the CRM in 2021, slow and fast scenarios until 2030 and a full rollout scenario.

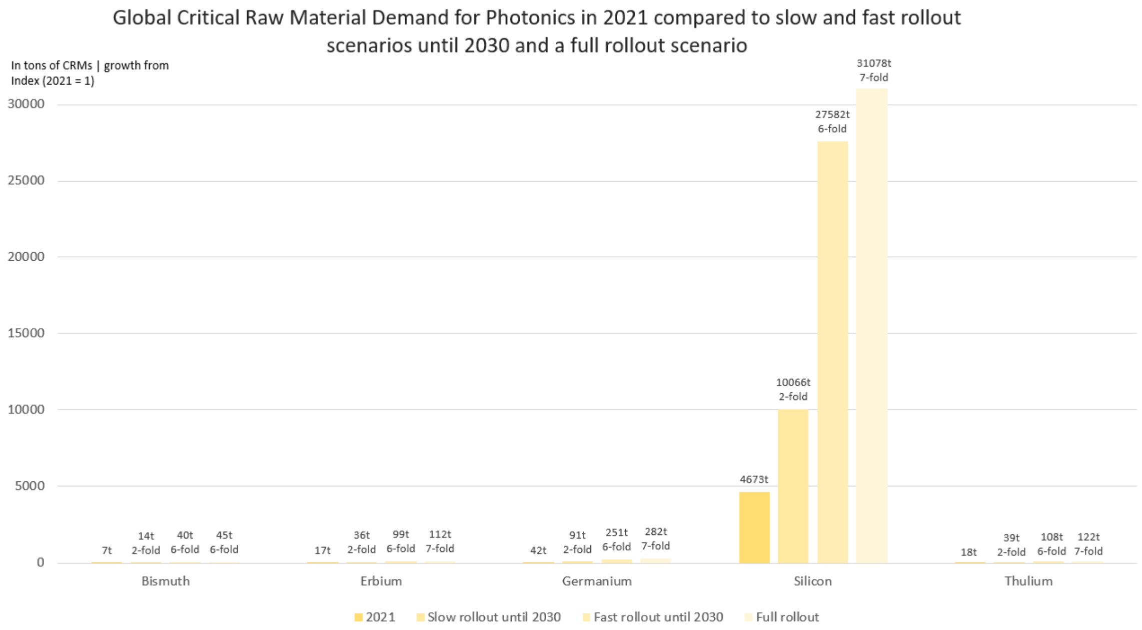


Figure 5.3: Global CRM demand for Photonics in 2021 compared to slow and fast rollout scenarios until 2030 and a full rollout scenario.

The five CRMs with the biggest weights in tons contained in Photonics are Si, Ge, Tm, Er and Bi in the respective order from highest to lowest. Compared to the index of 2021, the different CRMs are growing 2-fold under the slow rollout scenario until 2030, 6-fold under the fast rollout scenario until 2030 and 7-fold under a full rollout scenario.

5.2.3. Edge Computing – Demand Scenarios

In order to make forecasts for the amount of edge computing servers, firstly the amount of servers needed to be scaled up, followed by the portion of expected servers located at the edge. Detailed calculations can be found in Appendix I. In 2021, it is calculated that 2,7 million Edge Computing Servers are deployed worldwide.

Slow and fast rollout scenario of Edge Computing until 2030

For the slow rollout scenario, data of WBOC (2021) was taken. WBOC (2021) estimates that between 2020 and 2027, the Edge Server market will grow with a CAGR of 8,13%. This CAGR was taken and scaled up to 2030. For the fast rollout scenario, it was assumed that the calculated CAGR of 15% of servers deployed at the edge by Leopold (2020) is scaled up until 2030. This means, that numbers for 2025 – 2030 were calculated.

With a starting of 2,7 million servers in 2021 (Section, 2020), Table 5.5 represents the device developments of Edge Computing Servers under the two scenarios. Furthermore, the CRM demand development can be found in Appendix I.

Table 5.5: Amount of Edge Computing Servers under a slow and fast rollout scenario until 2030.

	In Million	Amount Edge Computing Servers until 2030 [in million]									
		2021	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Slow rollout scenario	Edge Servers	2,7	2,9	3,2	3,4	3,7	4	4,3	4,7	5	5,5
Fast rollout scenario	Edge Servers	2,7	3,1	3,6	4,1	4,7	5,4	6,2	7,2	8,3	9,5

Full global rollout of Edge Computing Servers

For the full rollout scenario, both servers shipped and servers deployed at the edge were scaled up to that point in time when both equal each other. This means that all servers that are shipped globally will be deployed at the edge. Detailed calculations can be found in Appendix I. Table 5.6 represents the amount of CRMs that would be required under the full global rollout scenario of Edge Computing Servers.

Table 5.6: Required material tons under a full global rollout of an Edge Computing Server.

CRMs	In tons	CRMs	In tons
Antimony Sb	107,65	Magnesium Mg	5.555,25
Boron B	15.247,06	Neodymium Nd	323.562,45
Barium Ba	14.287,36	Phosphorous P	1.736,45
Cobalt Co	37.969,02	Palladium Pd	23,95
Dysprosium Dy	41750,79	Ruthenium Ru	25,43
Erbium Er	0	Silicon Si	291.177,32
Gallium Ga	197,52	Tantalum Ta	6.709,75
Germanium Ge	0,91	Titanium Ti	14.287,36
Lithium Li	23.702,4	Tungsten W	0,49

Demand Comparison for the highest Weight containing CRMs in Edge Computing

The following Figure 5.4 shown comparisons of the demand for the CRM in 2021, slow and fast scenarios until 2030 and a full rollout scenario.

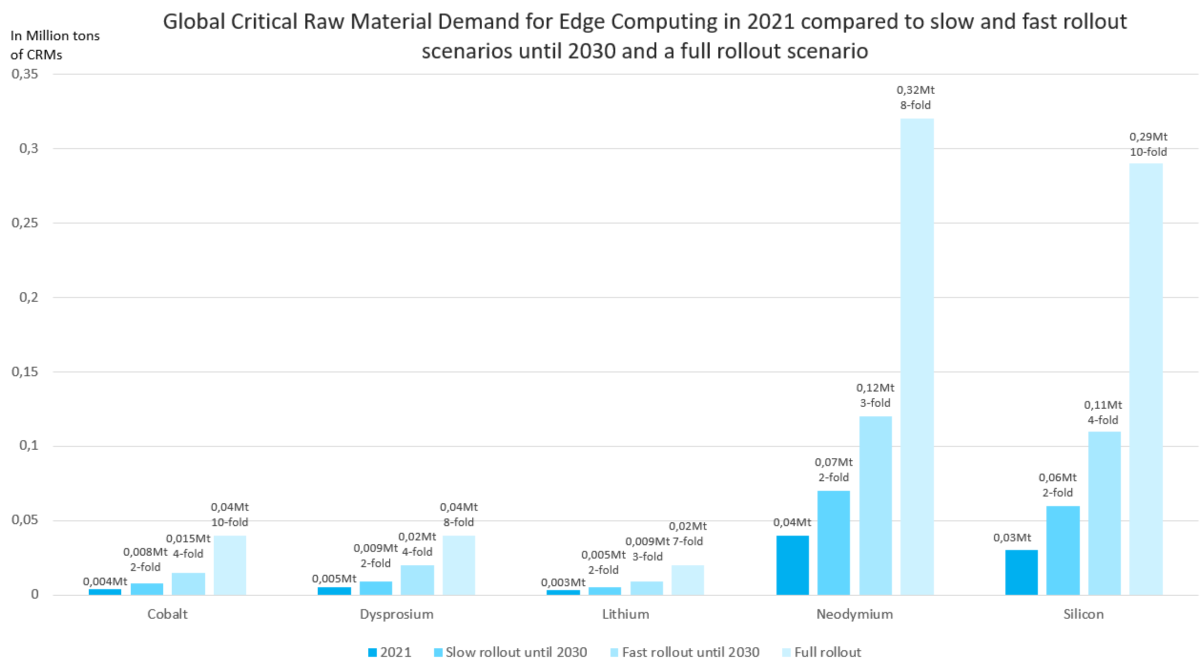


Figure 5.4: Global CRM demand for Edge Computing in 2021 compared to slow and fast rollout scenarios until 2030 and a full rollout scenario.

The five CRMs with the biggest weights in tons contained in Edge Computing are Nd, Si, Co, Dy and Li in the respective order from highest to lowest. Compared to the index of 2021, the different CRMs are growing 2-fold under the slow rollout scenario until 2030, between 3 to 4-fold under the fast rollout scenario until 2030 and between 7 to 10-fold under a full rollout scenario.

5.2.4. Quantum Technologies – Demand Scenarios

The slow and fast rollout scenarios were both developed together with Expert A for Quantum Communication (2021). Since Quantum Technologies are in a very early stage of development, it is difficult to predict on how many are already available in 2021. Thus, it was decided that the amount of devices in 2021 vary for both scenarios. Furthermore, according to Expert B for Quantum Communication (2021), the fast development is so rapidly, that it can be seen as a full rollout. Thus, no additional full rollout scenario was developed for Quantum Technologies. Additionally, it is worth to mention that the market for Quantum Technologies is approximately divided into 1/3 located in Europe, 1/3 in North America and 1/3 in Asia (Expert A for Quantum Communication, 2021). Additionally, the individual weights per quantum device can be found in Appendix J1.

Slow and fast rollout scenarios of Quantum Technologies until 2050

As part of the slow rollout scenario, it is estimated that in 2021, there are no Quantum Routers developed yet and only 300 Quantum Senders and Quantum Receivers increasing until 2050 (Expert A for Quantum Communication, 2021). As part of the fast rollout scenario, in 2021 an amount of 1.200 Quantum Senders and Quantum Receivers were estimated, scaling up very rapidly to a much higher number by 2050. In the below Table 5.7 the different Quantum device developments can be found.

Table 5.7: Amount of Quantum Communication devices until 2050 under a slow and fast rollout scenario.

Scenario	Device	Amount Device in [time]						
		2021	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Slow rollout scenario	Quantum Router	0	300	600	1200	2400	4800	9600
	Quantum Sender	300	600	1200	2400	4800	9600	19200
	Quantum Receiver	300	600	1200	2400	4800	9600	19200
Fast rollout scenario	Quantum Router	0	1.200	3.900	15.000	75.000	330.000	1.440.000
	Quantum Sender	1.200	3.900	15.000	75.000	330.000	1.440.000	6.300.000
	Quantum Receiver	1.200	3.900	15.000	75.000	330.000	1.440.000	6.300.000

The CRM demand development can be found in Appendix J2.

Demand Comparison for the highest Weight containing CRMs in Edge Computing

The following Figure 5.5 shown comparisons of the demand for the CRM in 2021, slow and fast scenarios until 2030 and a full rollout scenario.

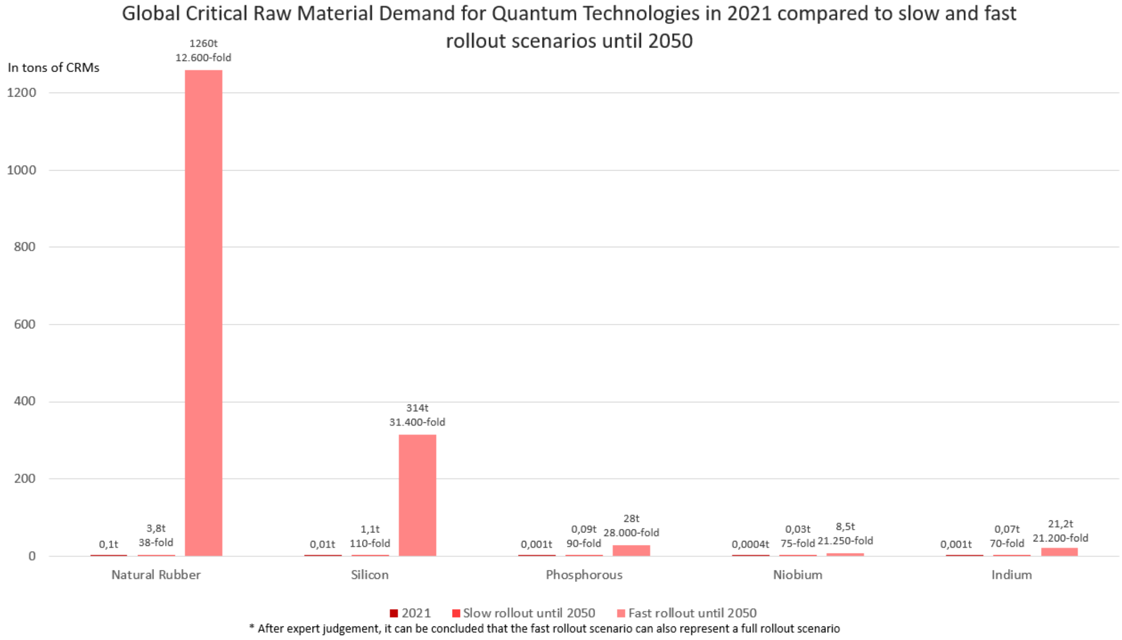


Figure 5.5: Global CRM demand for Quantum Technologies in 2021 compared to slow and fast rollout scenarios until 2030 and a full rollout scenario.

The five CRMs with the biggest weights in tons contained in Quantum Technologies are Natural Rubber, Si, P, In and Nb in the respective order from highest to lowest. Compared to the index of 2021, the different CRMs are growing differently between for the two scenarios. Under the slow rollout scenario until 2050, Natural Rubber is growing 38-fold and under a fast rollout scenario 12.600-fold respectively. In the case of Si, the growth is 110-fold and 31.400-fold under both scenarios. For P they are 90-fold and 28.000-fold growth. For Nb, they do have a 75-fold and 21.250-fold growth. Lastly, Indium will grow 70-fold under a slow rollout scenario and 21.200-fold under the fast rollout scenario.

5.2.5. Future Telecommunication Technologies – Demand Scenarios

As a first step, demand from each of the four technologies was aggregated to a total CRM demand under the three different scenarios compared to 2021 levels. The result of this can be found in Figure 5.6.

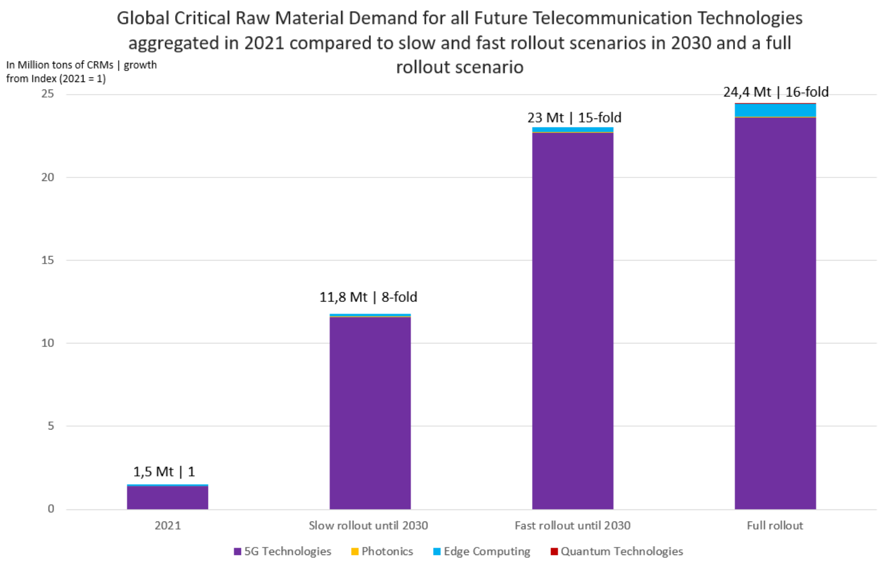


Figure 5.6: Global CRM demand per Future Telecommunication Technologies in 2021 compared to slow and fast rollout scenarios until 2030 and a full rollout scenario.

It can be expected that the demand for CRMs from the four technologies will rise between 8-fold to 15-fold under the slow and fast rollout scenarios and 16-fold under a full rollout scenario. In total numbers, that would be 11,8Mt, 23Mt and 24,4Mt respectively.

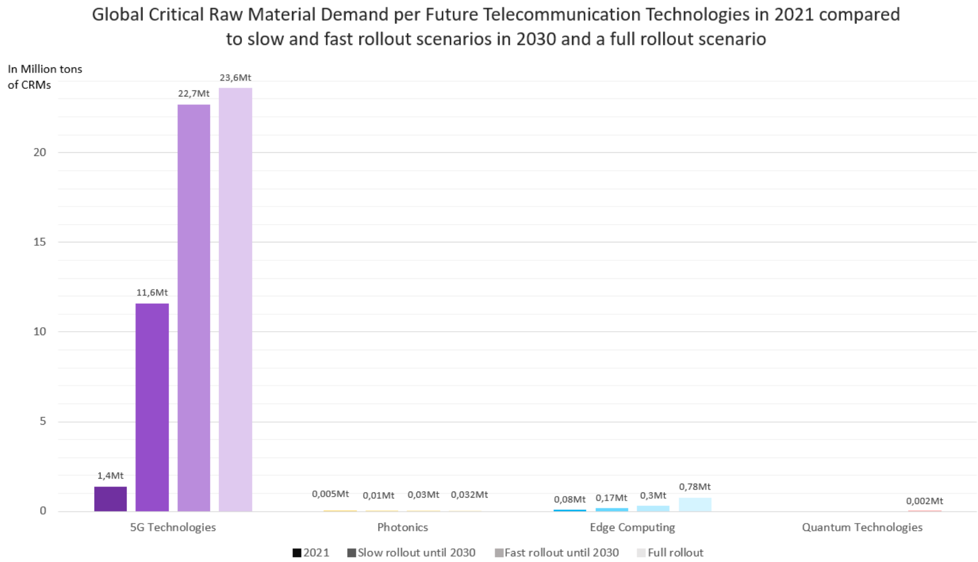


Figure 5.7: Global CRM demand per Future Telecommunication Technologies in 2021 compared to slow and fast rollout scenarios until 2030 and a full rollout scenario.

When looking at the above Figure 5.7, it becomes clear that the highest CRM demand by far is caused by the implementation of 5G Technologies. Even under the full rollout scenario, CRM demand from the other technologies does not exceed the demand of 5G. Following that, Edge Computing will require the most amounts of CRMs in tons. The amount of CRMs exceeds the amount of CRMs contained in Photonics and Quantum Technologies for every single scenario, as well as of the current demand in 2021. Quantum Technologies will require the least materials of all of the technologies.

When looking at the amounts in tons, as of today demand for CRMs lays in a range of 0t to 1,4Mt for the different technologies. For the slow rollout scenario, the range lays between 0t and 11,6Mt and for the fast rollout scenario between 0t and 22,7Mt respectively. Focusing on a full rollout scenario, the range lays in between 0,002Mt and 23,6Mt.

The following Figure 5.8 – 5.13 show the results of the demand development across all technologies and for the telecommunication industry as a whole.

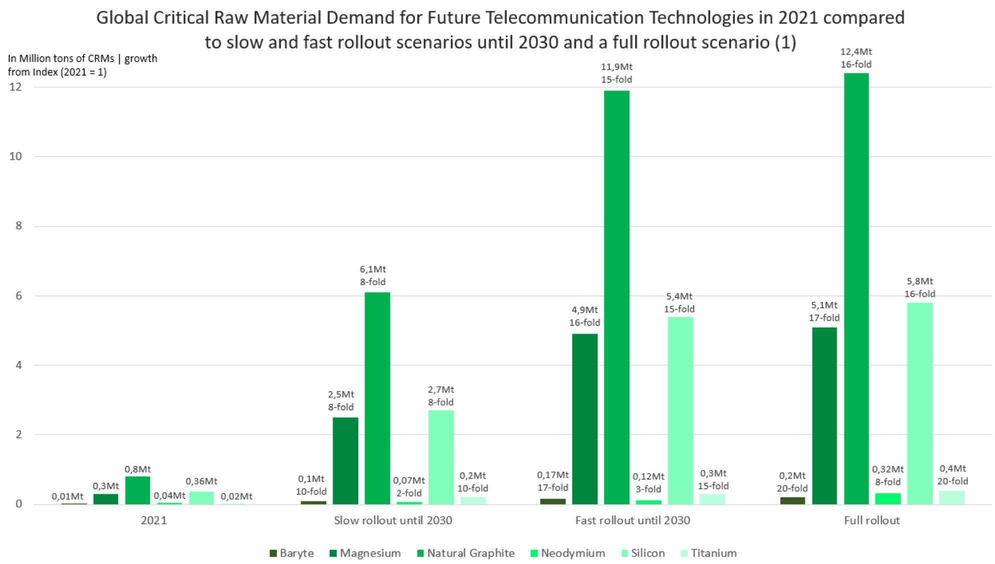


Figure 5.8: Global CRM demand for Future Telecommunication Technologies in 2021 compared to slow and fast rollout scenarios until 2030 and a full rollout scenario – Ba, Mg, Graphite, Nd, Si and Ti.

When aggregating all CRMs contained in all four future technologies, the six largest CRMs in quantity are from the biggest to the lowest Natural Graphite, Si, Mg, Ti, Nd and Ba. Generally, for all CRMs, a strong increase under the three scenarios can be discovered. Ba and Ti will see an increase between 10-fold and 20-fold depending on the scenario, Mg between 8-fold and 17-fold, Natural Graphite between 8-fold and 16-fold, Nd between 2-fold and 8-fold and Si between 9-fold to 16-fold.

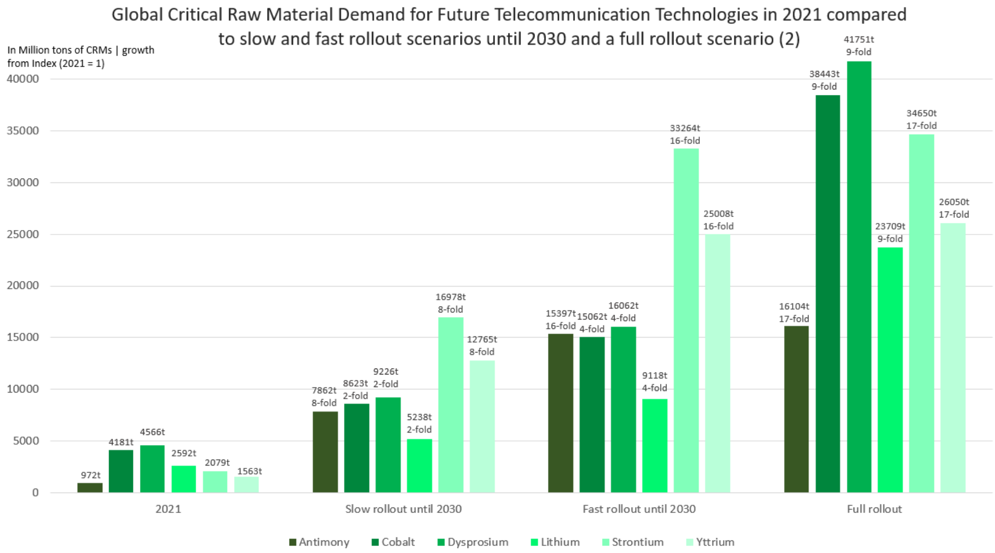


Figure 5.9: Global CRM demand for Future Telecommunication Technologies in 2021 compared to slow and fast rollout scenarios until 2030 and a full rollout scenario – Sb, Co, Dy, Li, Sr and Y.

Sb, Sr and Y will see an 8-fold to 17-fold increase and Co, Dy and Li an 2-fold to 9-fold increase depending on the scenario.

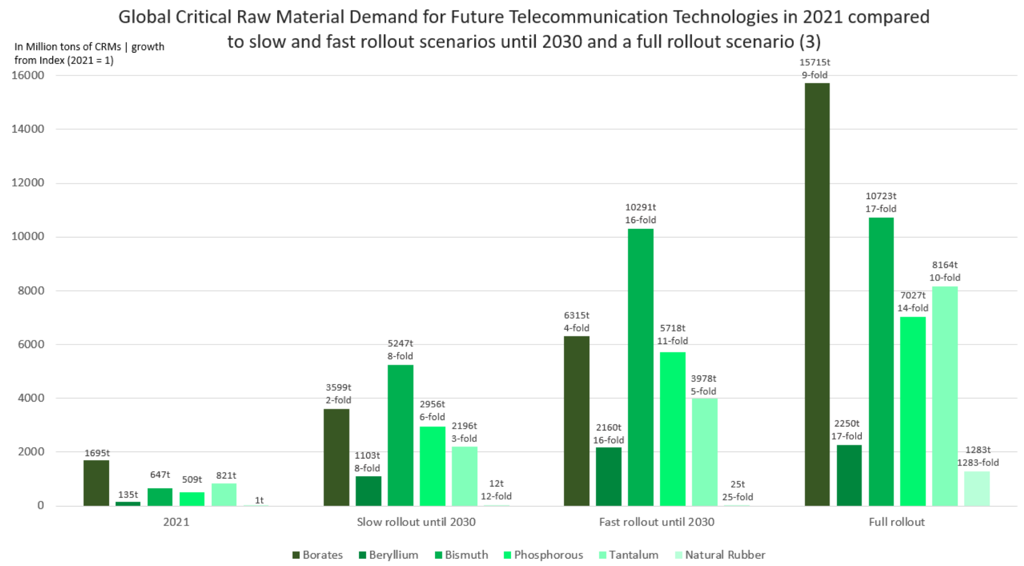


Figure 5.10: Global CRM demand for Future Telecommunication Technologies in 2021 compared to slow and fast rollout scenarios until 2030 and a full rollout scenario – B, Be, Bi, P, Ta and Natural Rubber.

B will see an 2-fold to 9-fold increase depending on the scenario, Be and Bi an 8-fold to 17-fold increase, P between 6-fold and 14-fold increase and Ta a 3-fold to 10-fold increase. Outstanding is the demand increase for Natural Rubber. While under the slow rollout scenario, 12-fold increase is expected and under the fast rollout scenario a 25-fold increase, this is rising strongly to 1.283-fold increase under the full rollout scenario.

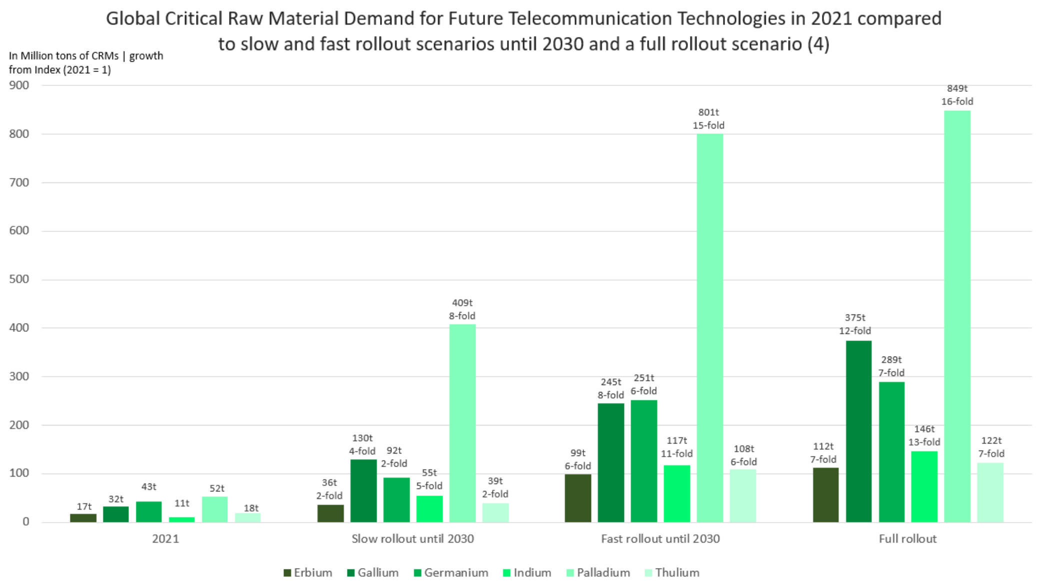


Figure 5.11: Global CRM demand for Future Telecommunication Technologies in 2021 compared to slow and fast rollout scenarios until 2030 and a full rollout scenario – Er, Ga, Ge, In, Pd and Tm.

A between 2-fold and 7-fold increase is expected for Er, 4-fold to 12-fold increase for Ga, 2-fold to 7-fold increase for Ge and Tm, 5-fold to 13-fold increase for In and 8-fold to 16-fold increase for Pd.

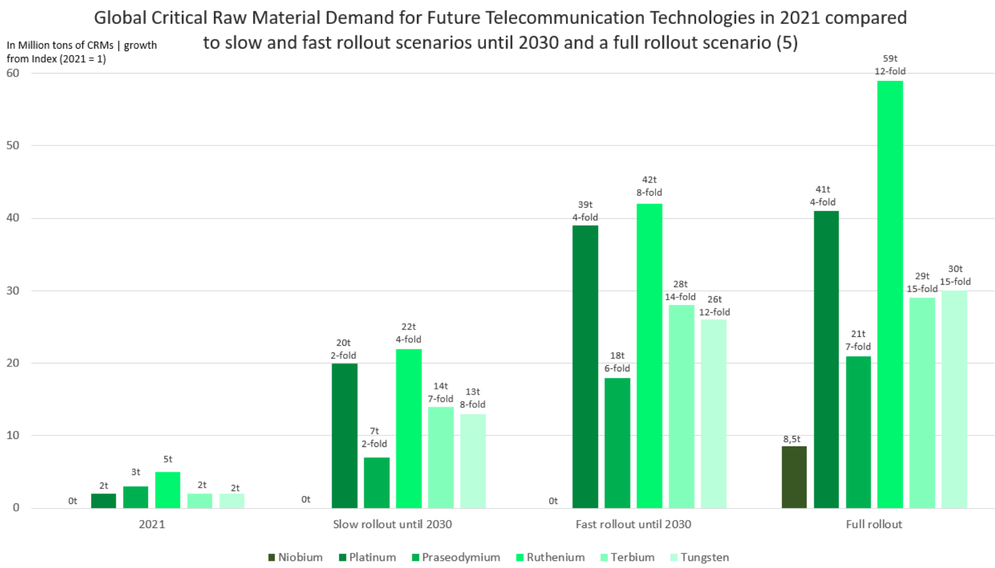


Figure 5.12: Global CRM demand for Future Telecommunication Technologies in 2021 compared to slow and fast rollout scenarios until 2030 and a full rollout scenario – Nb, Pt, Pr, Ru, Tb and W.

In the case of Nb, 8,5t would solely be required under the full rollout scenario. For Pt, a demand increase is expected between 2-fold to 4-fold, for Pr between 2-fold and 7-fold, for Ru between 4-fold and 12-fold, for Tb between 7-fold to 15-fold and for W between 8-fold and 15-fold increase.

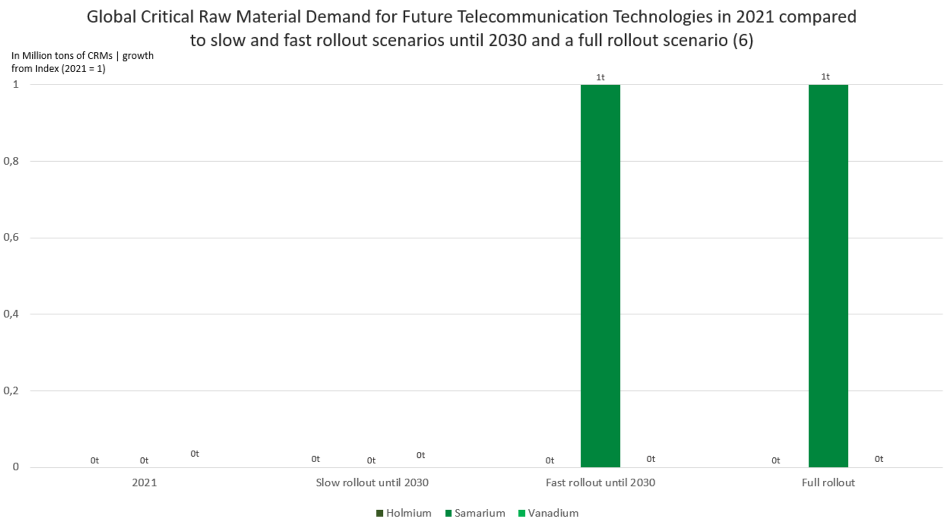


Figure 5.13: Global CRM demand for Future Telecommunication Technologies in 2021 compared to slow and fast rollout scenarios until 2030 and a full rollout scenario – Ho, Sm and V.

For the last three CRMs, solely conclusions on Sm can be drawn. Both, under the fast rollout as well as the full rollout, demand is expected to be 1t.

5.3. Material Demand arising from other Sectors

There are three sectors, which include the most CRMs in their various applications: The energy sector, the transport sector and the electronics & telecom sector (Monnet et al., 2018). This shows that in the future, demand will not only arise from the telecom sector, but also from other sectors, making the demand and supply situation even more problematic.

The IEA (2021) investigated into the demand for the energy sector as well as the transport sector, focusing on electric vehicles (EVs). The focus materials included Ch, Cu, Co, Graphite, Manganese, Mo, Ni, Li, REEs, Zn, PGMs, Si and Al (IEA, 2021). Amongst them, Co, Li, REEs and PGMs are CRMs and were also analyzed as part of this study. Especially the CRMs Dy, Nd, Pd, Ru, Si, Tb, Tm and Y are thus mostly present in the three different sectors.

According to the IEA (2021), in the transportation sector, an EV requires relatively larger amounts of Li, Co, Graphite and REEs. Furthermore, in the energy sector, wind turbines require REEs and solar PV requires Si (IEA, 2021). Looking at the material demand, the IEA (2021) developed several scenarios, amongst one reflects the 2°C goal of the Paris Agreement and another one a net-zero scenario. The results include a 4-fold increase of mineral requirements specifically for the clean energy transition until the year of 2040 under the 2°C scenario and in the case of aiming for net-zero, a 6-fold increase (IEA, 2021). In total numbers, this means an increase from around 7Mt to 28Mt by 2040 under the 2°C scenario or 42Mt under the net-zero scenario by 2050 (IEA, 2021). When looking at the results for the telecommunication sector (Figures 5.6), under the slow, fast and full rollout scenario, a much higher CRM demand is expected with 8-fold, 15-fold and 16-fold respectively until 2030. In total numbers, this means an increase from 1,5Mt in 2021 to 11,8Mt until 2030 under the slow rollout scenario and 23Mt under the fast rollout scenario until 2030. Looking at a hypothetical full rollout scenario, around 24,4Mt would be required. Comparing those total numbers, a higher mineral demand is arising from the transportation and energy sector, than from the telecommunication sector, however the increase is expected to be higher throughout the years for the telecommunication sector.

Analyzing the highest demand arising from the individual minerals for the two sectors, a 42-fold increase for Li can be expected under the 2°C scenario until 2040, followed by 25-fold increase for Graphite, 21-fold increase for Co and 7-fold increase for REEs (IEA, 2021). Going into more detail about REEs, IEA (2021) predicted a 2-fold increase of Nd demand until 2040 or a 3-fold increase until 2040 depending on the scenarios. Comparing this demand with CRM demand from the telecommunication sector, under the slow rollout scenario until 2030, the Li demand is expected to increase 2-fold under the slow demand scenario until 2030, 4-fold under the fast demand scenario until 2030 and 9-fold under the full rollout scenario. Compared to the 42-fold increase from the other two sectors, the demand from the telecommunication sector will be relatively low. In the case of Graphite, an 8-fold increase, 15-fold or 16-fold increase is expected under the three scenarios for the telecommunication industry. Also here, the 25-fold increase above is much higher. For Co, 2-fold increase, 4-fold increase and 9-fold increase is expected, compared to a 21-fold increase for the other two sectors. This again shows, that relatively little Co will be required compared to the telecommunication sector. REEs were not aggregated as part of this study, however looking at some CRMs, the demand rise looks the following: Dy (2-fold, 4-fold, 9-fold); Nd (2-fold, 3-fold, 8-fold); Tb (7-fold, 14-fold, 14-fold), Tm (2-fold, 6-fold, 7-fold) and Y (8-fold, 16-fold, 17-fold). This shows that the demand for at least some REEs is increasing higher for the telecommunication sector than for the other two sectors.

Chapter 6: Demand in the perspective of current supply

In order to put the demand for CRMs arising from the deployment of future telecom technologies into perspective, the demand in 2030 and 2050 was compared to the annual world production rates for these raw materials. This answers the third research question *How does the arising demand for Critical Raw Materials from future telecommunications technologies compare to the current available supply?* The raw data used for that can be retrieved from Appendix K.

6.1. 5G Technologies – Supply Comparison

When comparing the demand in 2030 after both a slow rollout and a fast rollout scenarios of 5G Technologies, some CRM are exceeding the annual world production rates and some require high shares of annual world production rates. This can be seen in the following Figure 6.1 – 6.4.

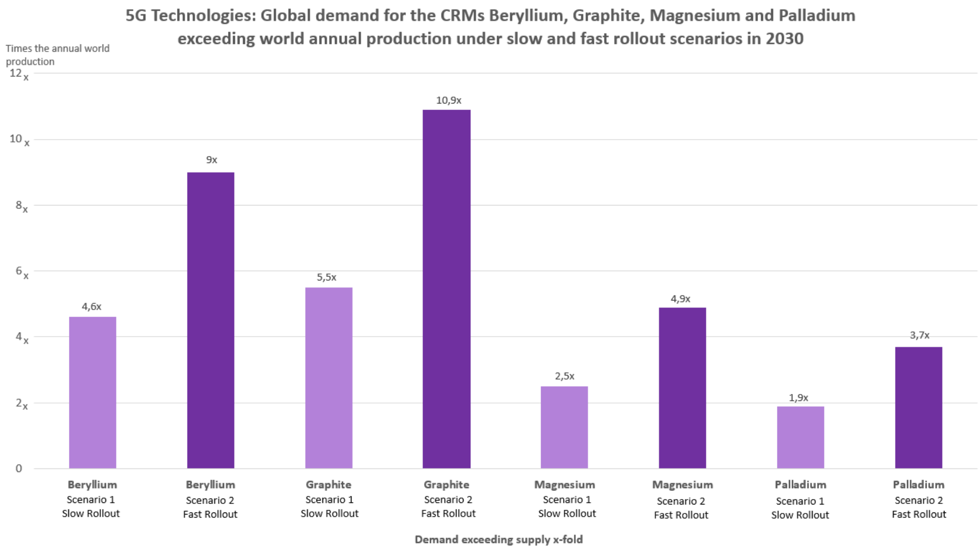


Figure 6.1: 5G Technologies: Global demand for the CRMs Be, Graphite, Mg and Pd exceeding world annual production rates under slow and fast rollout scenarios in 2030.

It can be identified that for both slow and fast rollout scenarios, for Be, Graphite, Mg and Pd, the required demand in 2030 will exceed annual production rates. This is especially drastical for Be and Graphite under the fast rollout scenario, since demand exceeds supply 9-fold and 10,9 fold respectively. However also in the case of the remaining slow rollout scenarios and the CRMs Mg and Pd, demand exceeds supply between 1,9-fold to 5,5-fold.

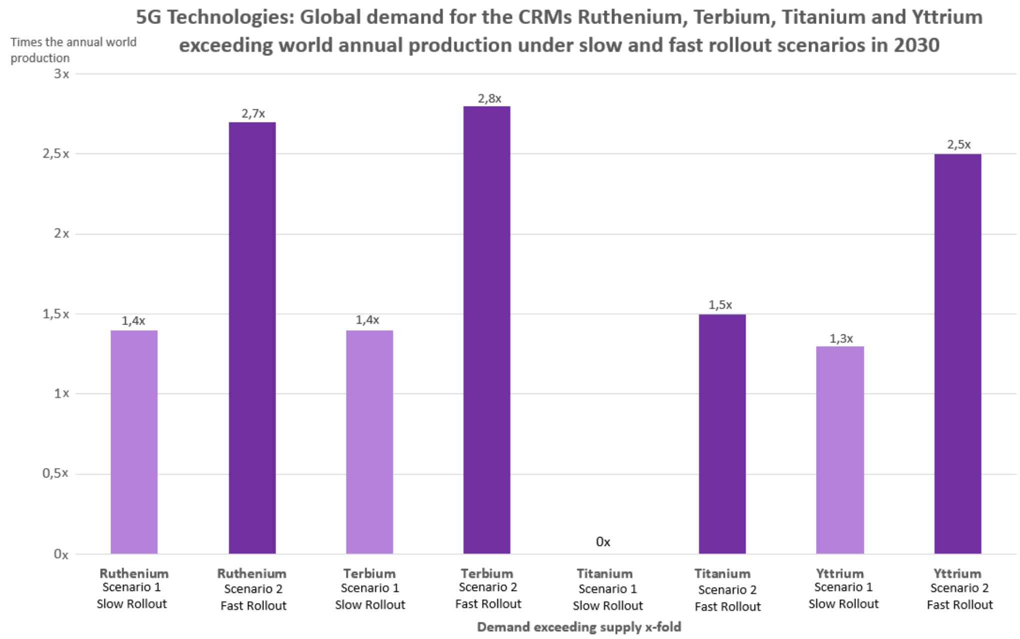


Figure 6.2: 5G Technologies: Global demand for the CRMs Ru, Tb, Ti and Y exceeding world annual production rates under slow and fast rollout scenarios in 2030.

In the case of Ru, Tb and Y under a fast rollout scenario, demand will exceed supply 2,7-fold, 2-8-fold and 2,5-fold respectively. Under the slow rollout scenario for Ru and Tb, demand will exceed 1,4-fold and for Yttrium around 1,3-fold. Solely for Titanium, under a slow rollout scenario, demand will not exceed supply.

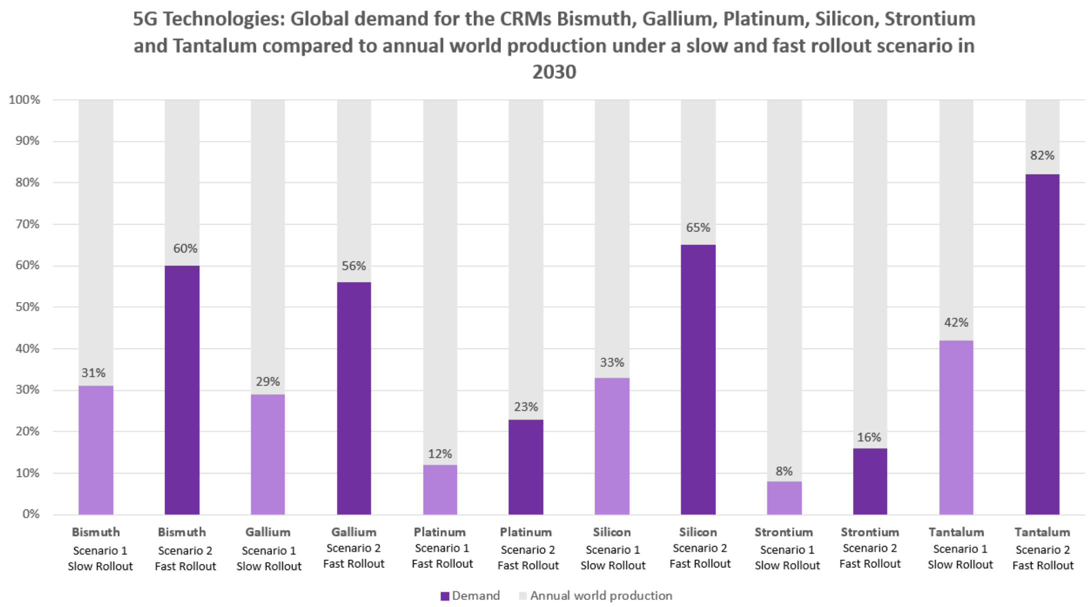


Figure 6.3: 5G Technologies: Global demand for the CRMs Bi, Ga, Pt, Si, Sr and Ta compared to world annual production rates under slow and fast rollout scenarios in 2030.

When looking at the fast rollout scenario, it becomes clear that for almost all of the above shown CRMs, in case of a fast rollout scenario, the material demand for 5G Technologies is at least half the actual annual world production rate. For Bi, around 60% of the annually produced material would be needed, for Ga around 56%, for Si around 65% and for Ta even 82%. However, also for the remaining

CRMs, Pt and Sr, a high produced material share would be required for rolling out 5G. In the case of a slow rollout scenario, between 8% to 42% of the annual material resources would be required.

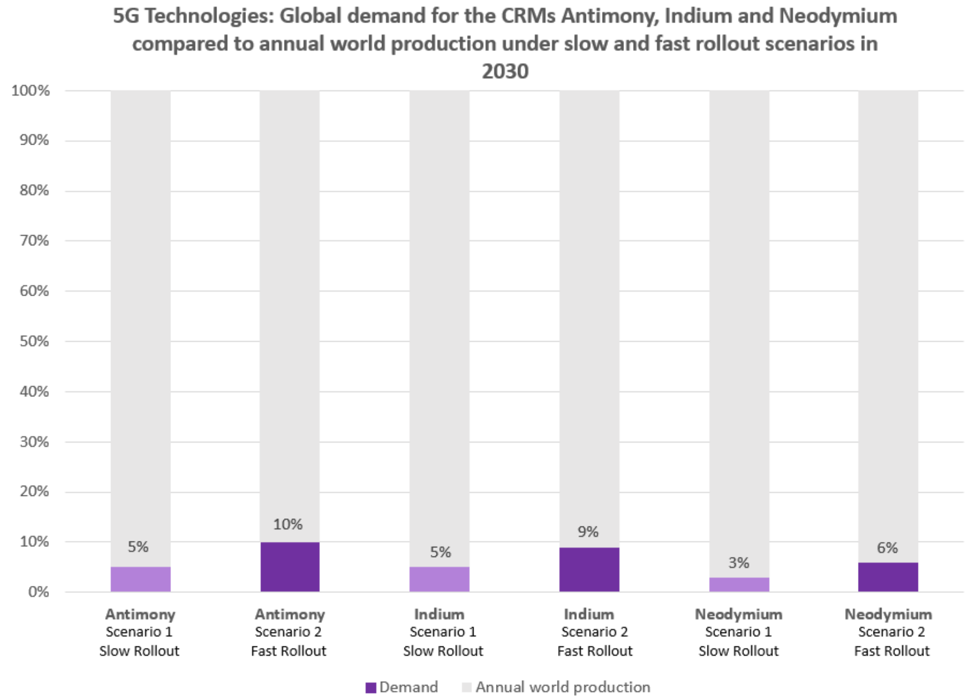


Figure 6.4: 5G Technologies: Global demand for the CRMs Sb, In and Nd compared to world annual production rates under slow and fast rollout scenarios in 2030.

Required annually produced materials for the implementation of 5G Technologies would require between 3%-10% of Sb, In or Nd depending on the scenario.

Additionally, the third scenario focused on a full global rollout for 5G Technologies and it was investigated which entire demand this would cause. In the following Figure 6.5 – 6.6 the results of that scenario can be found.

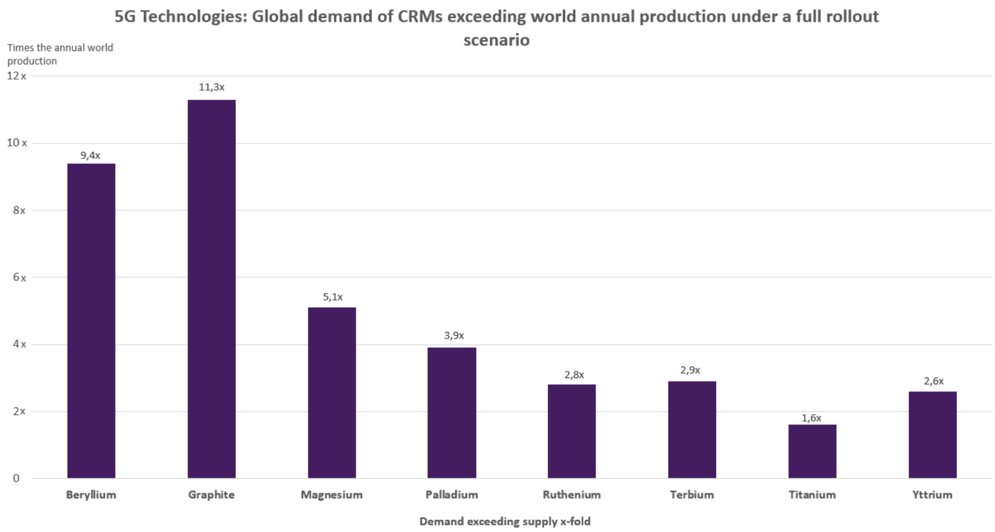


Figure 6.5: 5G Technologies: Global demand of CRMs exceeding world annual production under a full rollout scenario.

In the case that 5G Technologies would be fully rolled out globally, the CRMs Be, Graphite, Mg, Pd, Ru, Tb, Ti and Y would all exceed annual production rates. In the case of Graphite, this would mean 11,3-fold higher demand than supply, for Be 9,4-fold higher demand. However, also for the remaining CRMs, demand would exceed supply between 1,6-fold for Ti and 5,1-fold for Mg.

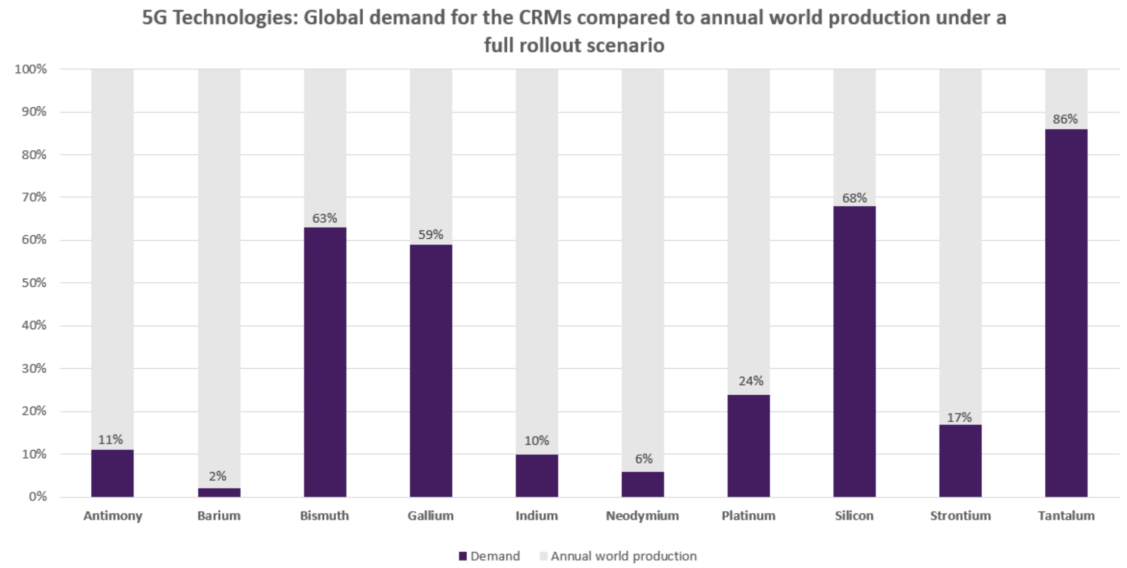


Figure 6.6: 5G Technologies: Global demand of CRMs compared to world annual production under a full rollout scenario.

In the case of fully rolling out 5G Technologies globally, for some CRMs a vast majority of materials produced annually would be required. In the case of Ta, around 86% of supply would be required, followed by 68% for Si, 63% for Bi and 59% for Ga. For the remaining CRMs Sb, Ba, In, Nd, Pt and Sr however, required supplied resources would vary between 2% for Ba and 24% for Pt.

6.2. Photonics – Supply Comparison

When comparing the demand in 2030 after both a slow rollout and a fast rollout scenarios of Photonics, some CRM are exceeding the annual world production rates and some require high shares of annual world production rates. This can be seen in the following Figure 6.7 – 6.8.

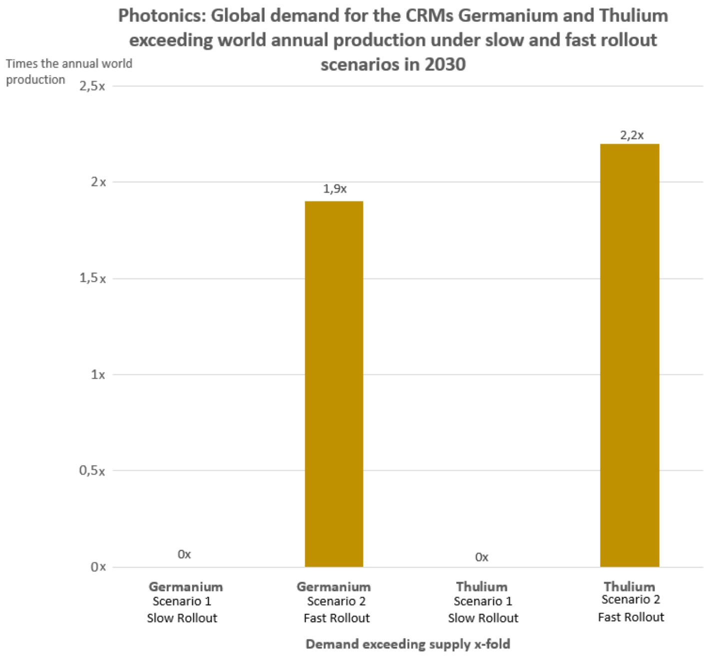


Figure 6.7: Photonics: Global demand for the CRMs Ge and Tm exceeding world annual production rates under slow and fast rollout scenarios in 2030.

For the two CRMs Ge and Tm, under a fast rollout scenario, demand exceeds the annual world production rates by 1,9-fold and 2,2-fold respectively. This is not the case for slow rollout scenario.

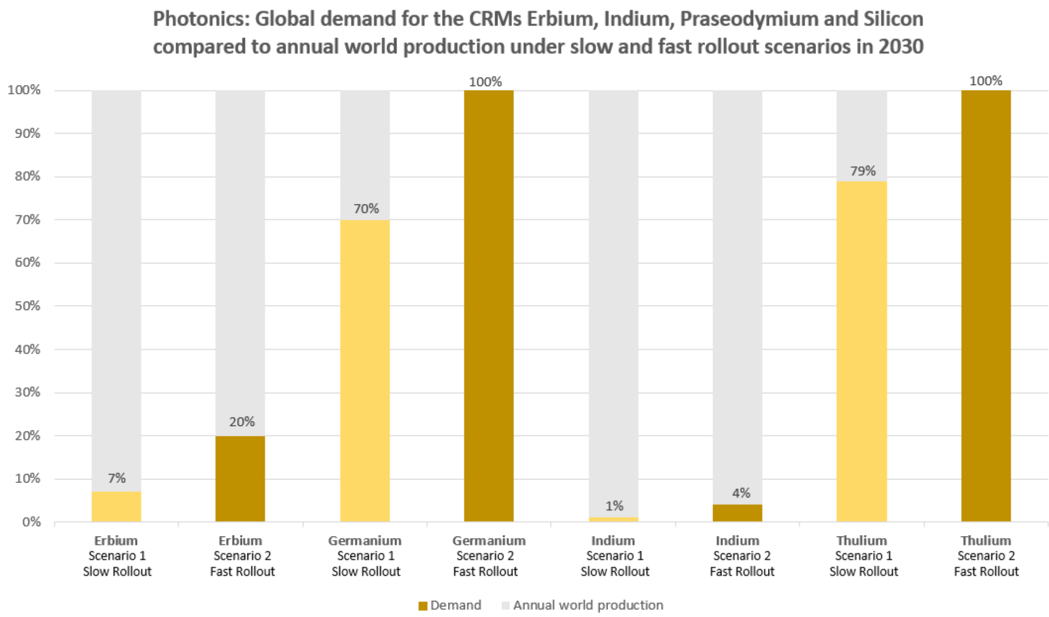


Figure 6.8: Photonics: Global demand for the CRMs Er, Ge, In and Tm compared to world annual production rates under slow and fast rollout scenarios in 2030.

In the case of several CRMs, the global demand is relatively high compared to the annual world production rates. This is the case especially for the CRMs Ge and Tm, which under a slow rollout scenario would require 70% of the annual supply and 79% respectively. This represents the slow rollout scenarios of Figure 6.9 above. Furthermore, under a fast rollout scenario, Photonics would require an Er demand of 20% of annual supply and an In demand of 4% of the annual supply. In the case of a slow rollout scenario, these percentages are relatively lower.

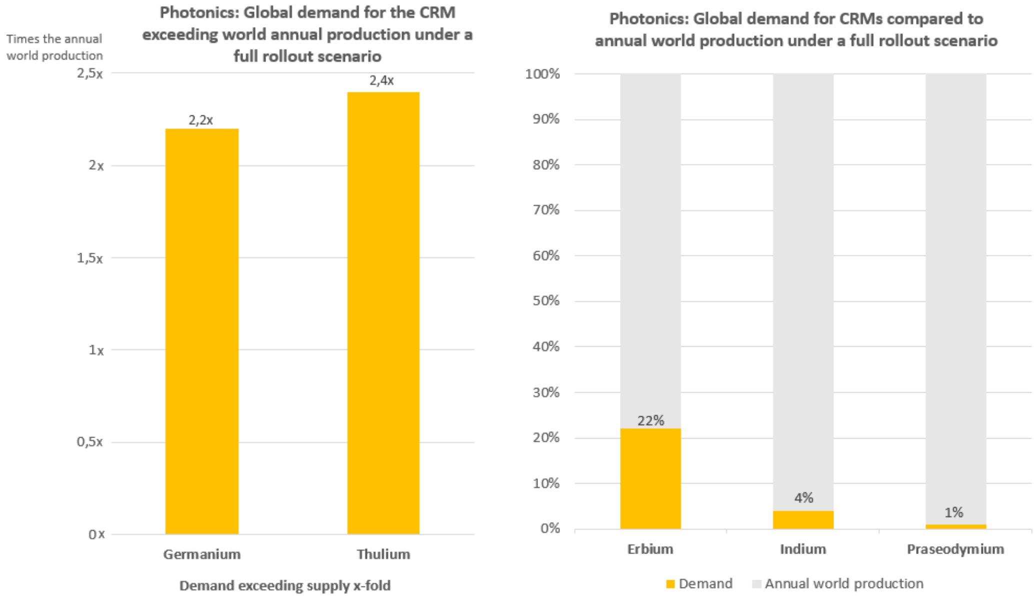


Figure 6.9: Photonics: Global demand of CRMs exceeding and compared to world annual production under a full rollout scenario.

When looking at a full rollout scenario of Photonics, Ge and Tm would even more exceed the world annual production, by 2,2-fold and 2,4-folg respectively. For the CRMs Er, In and Pr, the demand would require 22%, 4% and 1% of the annual world production of those CRMs.

6.3. Edge Computing – Supply Comparison

When comparing the demand in 2030 after both a slow rollout and a fast rollout scenarios of Edge Computing Servers, some CRM are exceeding the annual world production rates and some require high shares of annual world production rates. This can be seen in the following Figure 6.10 – 6.11.

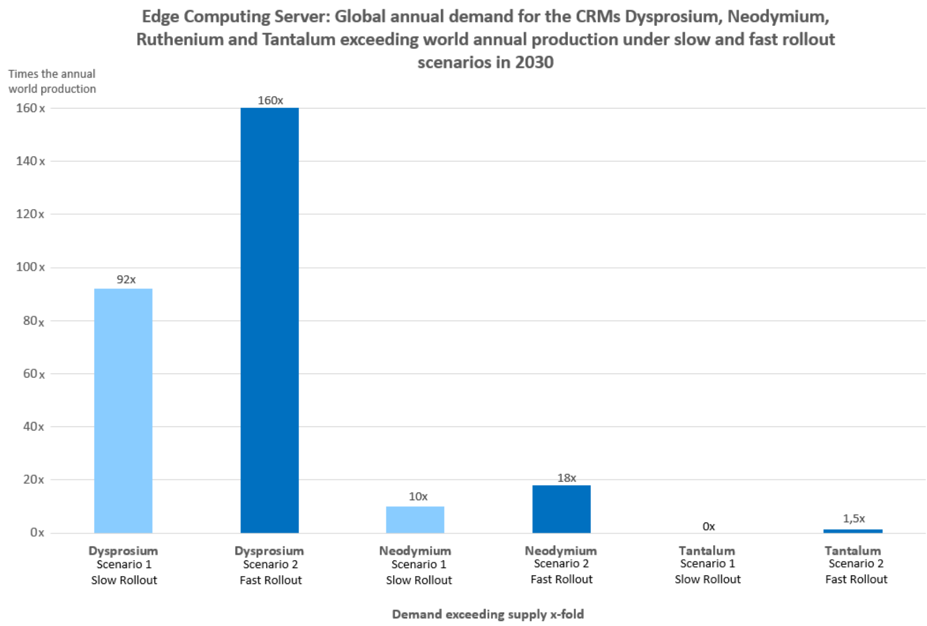


Figure 6.10: Edge Computing Server: Global demand for the CRMs Dy, Nd and Ta exceeding world annual production rates under slow and fast rollout scenarios in 2030.

When looking at an Edge Computing Server, it is remarkable that there seems to be a big problem with Dy. Under a slow rollout scenario Dy demand exceeds world annual production rates by 92-fold and in the case of a fast rollout scenario by even 160-fold. Additionally, also Nd can be considered problematic, since under a slow rollout scenario, demand would exceed world annual production rates 10-fold and under a fast rollout scenario 18-fold. In the case of Ta, solely under a fast rollout scenario, demand would exceed world annual production rates by 1,5-fold.

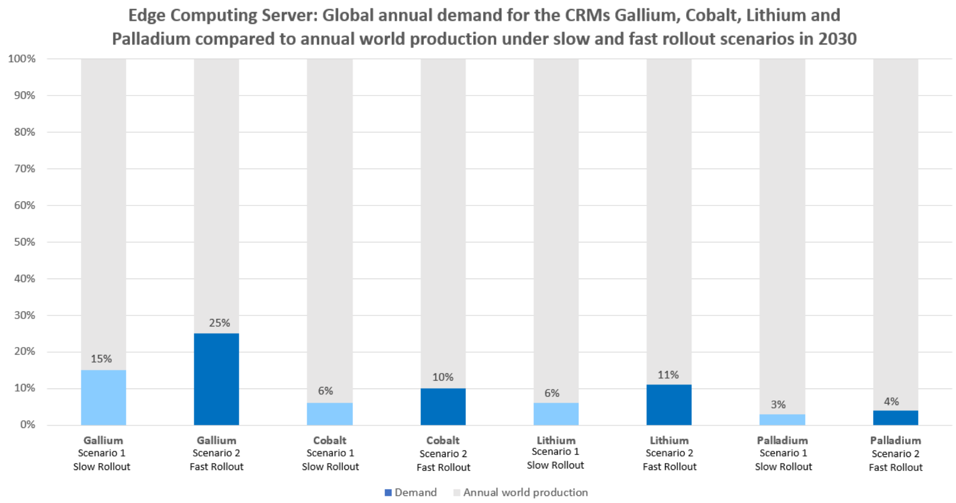


Figure 6.11: Edge Computing Server: Global demand for the CRMs Ga, Co, Li and Pd compared to world annual production rates under slow and fast rollout scenarios in 2030.

Under a fast rollout scenario, the demand of the CRMs Ga, Co, Li and Pd will lay between 4% and 25% of annual world production rates. In the case of a slow rollout scenario, it lays between 3% and 15% for the respective CRMs.

The following Figures 6.12 – 6.13 show the results for the full rollout scenario.

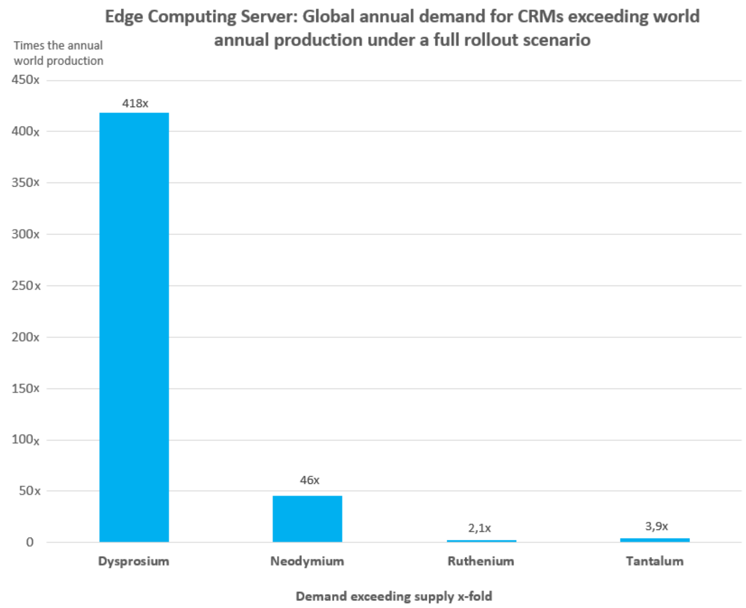


Figure 6.12: Edge Computing Server: Global demand of CRMs exceeding world annual production under a full rollout scenario.

Under a full rollout scenario, Dy would again have an immense impact. It would require 418 times more resources annually than the annual world production supply. Furthermore, also in the case of Nd, demand would exceed supply 46-fold. Additionally, Ta would exceed 3,9-fold and also Ru would start causing a problem, requiring 2,1-fold the annual world production.

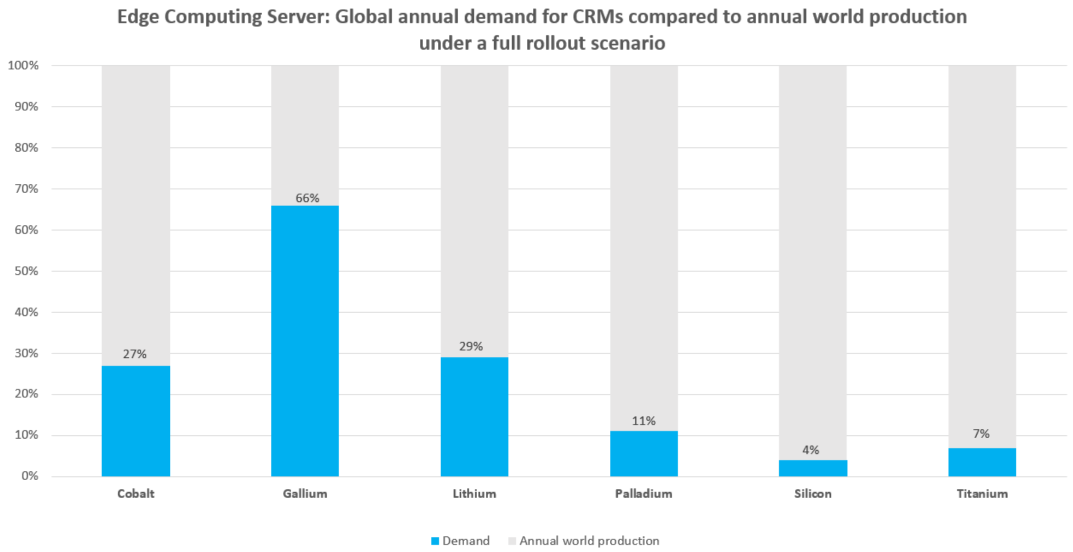


Figure 6.13: Edge Computing Server: Global demand of CRMs compared to world annual production under a full rollout scenario.

In the case of a full rollout scenario, the required share of world annual production caused by the demand of the CRMs Co, Ga, Li, Pd, Si and Ti would lay between 4% for Si and 66% for Ga. Li would require 29% of the world annual supply, Co would require 27% and Pd would require 11%.

6.4. Quantum Technologies – Supply Comparison

When comparing the demand in 2050 after both a slow rollout and a fast rollout scenario of Quantum Technologies, the demand is rather low compared to the world annual production. This can be seen in the following Figure 6.14.

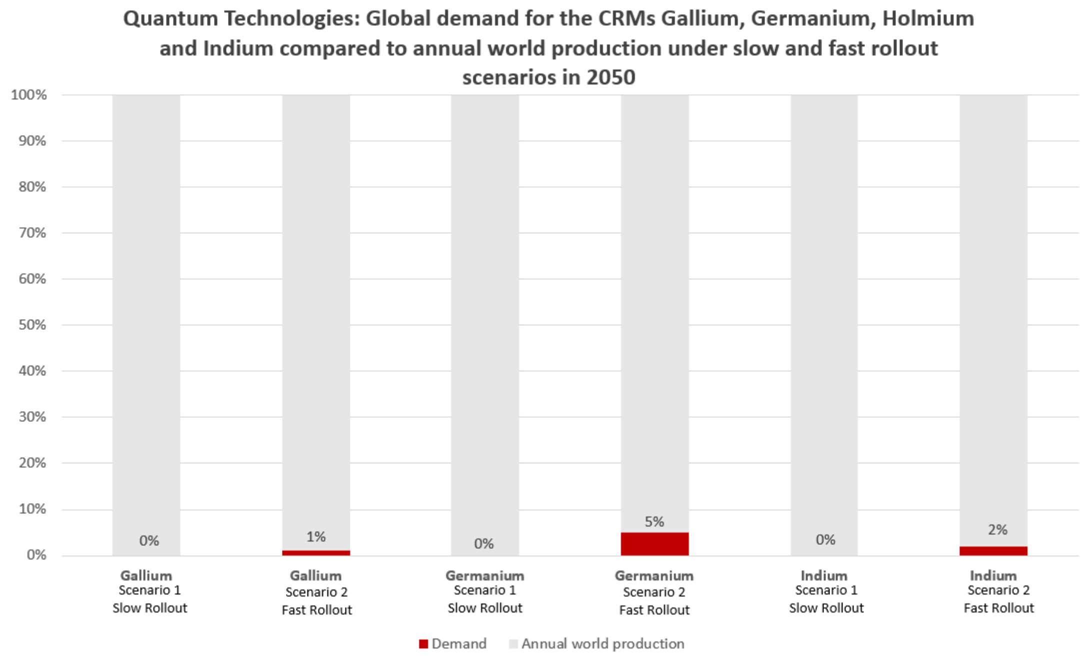


Figure 6.14: Quantum Technologies: Global demand for the CRMs Ga, Ge and In compared to world annual production rates under slow and fast rollout scenarios in 2050.

In the case of Quantum Technologies, solely three CRMs, Ga, Ge and In will have slightly higher resource-related impacts until 2050. Under a slow rollout scenarios only extremely small demand will arise through the implementation of the technology. Under a fast rollout scenario, which can basically also be considered a full rollout scenario, Ga will require 1% of the annual world supply, Ge will require 5% and In will require 2%.

6.5. Future Telecommunication Technologies – Supply Comparison

In order to draw conclusions on the whole future of technologies in the telecommunication industry, The amount of tons for the individual CRMs of each scenario was added up. In the case of Quantum Technologies, amount of tons in the year 2030 were taken, instead of 2050, which was the actual time frame for the implementation of Quantum Technologies. Additionally, for the full rollout scenario, regardless of time frames, amounts of tons were added up to show a full picture of the CRM demand compared to the world annual production rates. The results can be found in Figure 6.15 – 6.18.

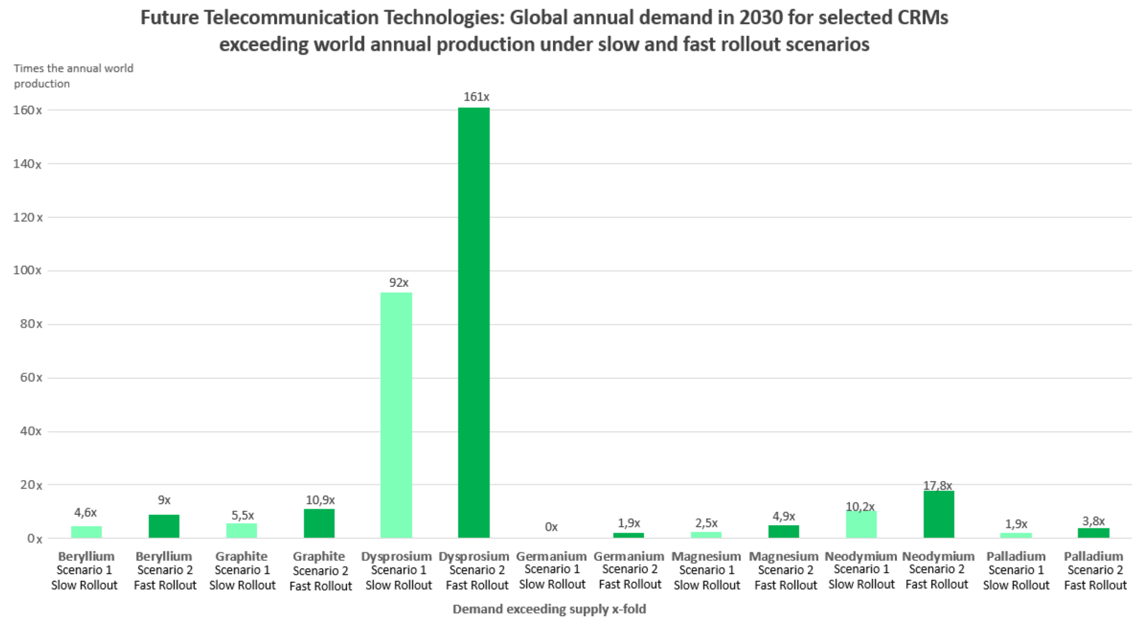


Figure 6.15: Future Telecommunication Technologies: Global demand of the CRMs Be, Graphite, Dy, Ge, Mg, Nd and Pd in 2030 exceeding world annual production under slow and fast rollout scenarios.

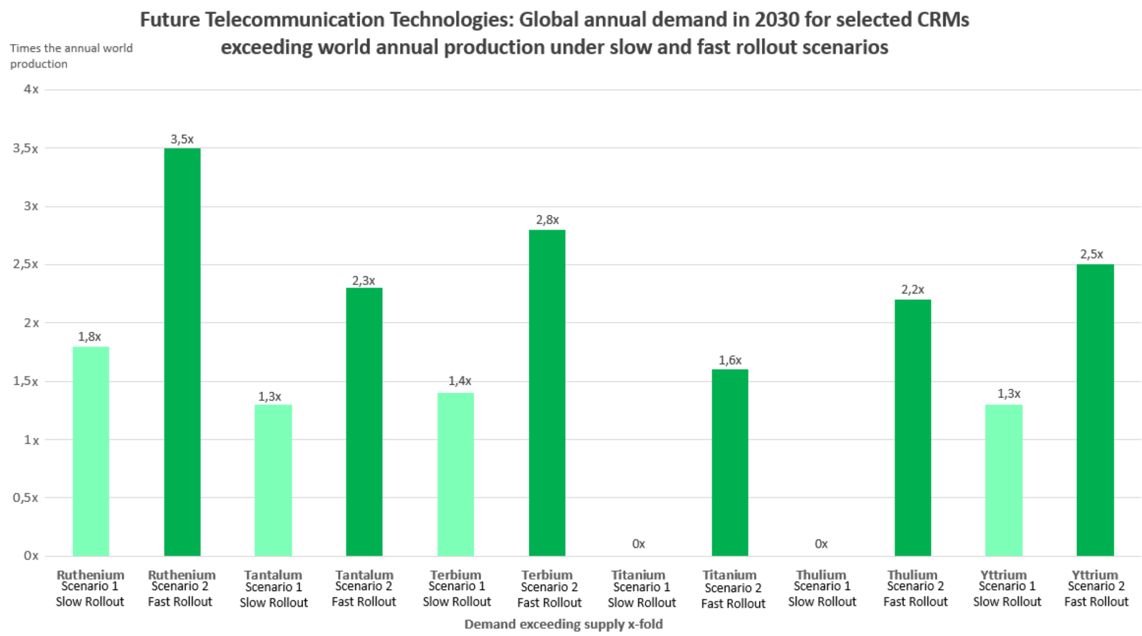


Figure 6.16: Future Telecommunication Technologies: Global demand of the CRMs Ru, Ta, Tb, Ti, Tm and Y in 2030 exceeding world annual production under slow and fast rollout scenarios.

When looking at the demand of CRMs for all future telecommunication technologies under the slow and fast rollout scenarios, for 10 under the slow rollout scenario and 13 CRMs under the fast rollout scenario, demand exceeds world annual production rates. Especially in the case of Dy, under a fast rollout scenario, demand exceeds supply 161-fold and for the slow rollout scenario 92-fold. In the case of Graphite and Nd, demand exceeds annual world production rates by 10,9-fold and 17,8-fold respectively under a fast rollout scenario and under a slow rollout scenario still 5,5-fold and 10,2-fold. For the remaining CRMs and the two rollout scenarios, demand exceeds supply between 1,3-fold and 9-fold. Solely in the slow rollout scenario until 2030, for the CRMs Ge, Ti and Tm, the demand does not exceed the supply.

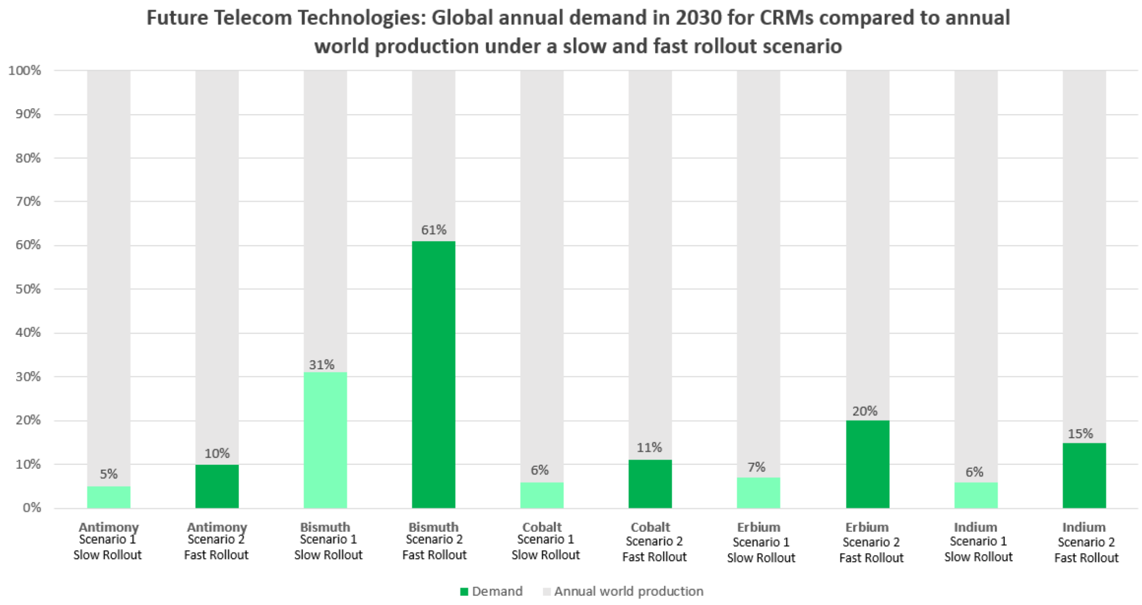


Figure 6.17: Future Telecommunication Technologies: Global demand of the CRMs Sb, Bi, Co, Er and In in 2030 compared to world annual production under slow and fast rollout scenarios.

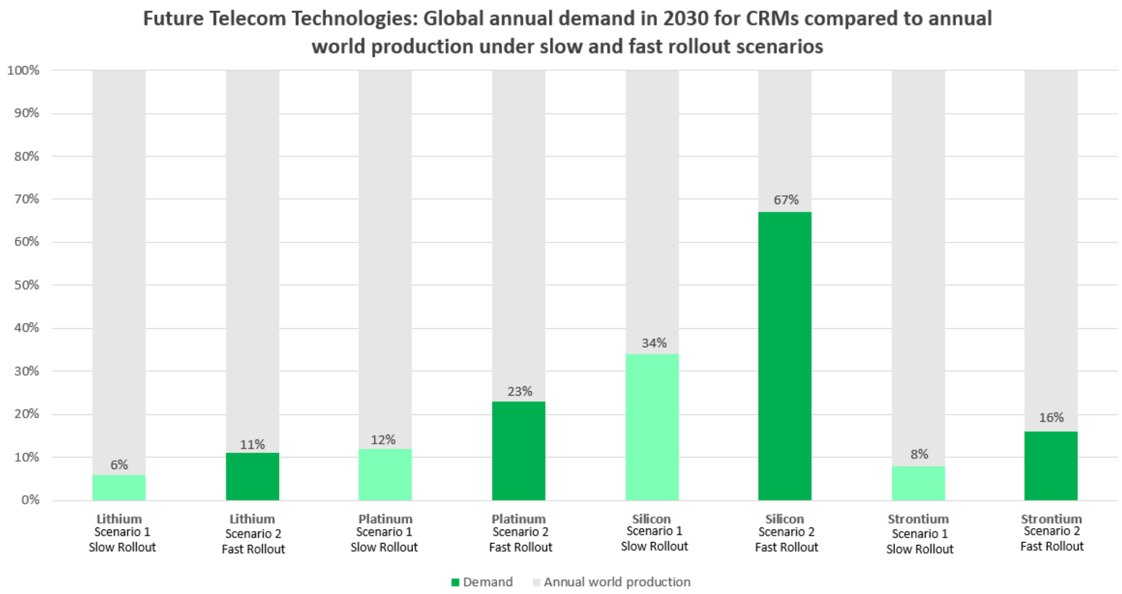


Figure 6.18: Future Telecommunication Technologies: Global demand of the CRMs Li, Pt, Si and Sr until 2030 compared to world annual production under slow and fast rollout scenarios.

When looking at the slow and fast rollout scenarios, when demand does not exceed supply, still huge shares of supply would be required to meet the demand for the future telecommunication technologies. Under a fast rollout scenario, Bi would require 61% of the annual world production and Si would require 67%. However, even under slow rollout scenarios, demand would still lay at 31% and 34% respectively. For the remaining CRMs, under the fast rollout scenario, the range lays between 10% and 23% of supply required. For the slow rollout scenarios, the range lays between 5% - 12%.

The following Figure 6.19 – 6.20 show the results for the full rollout scenario.

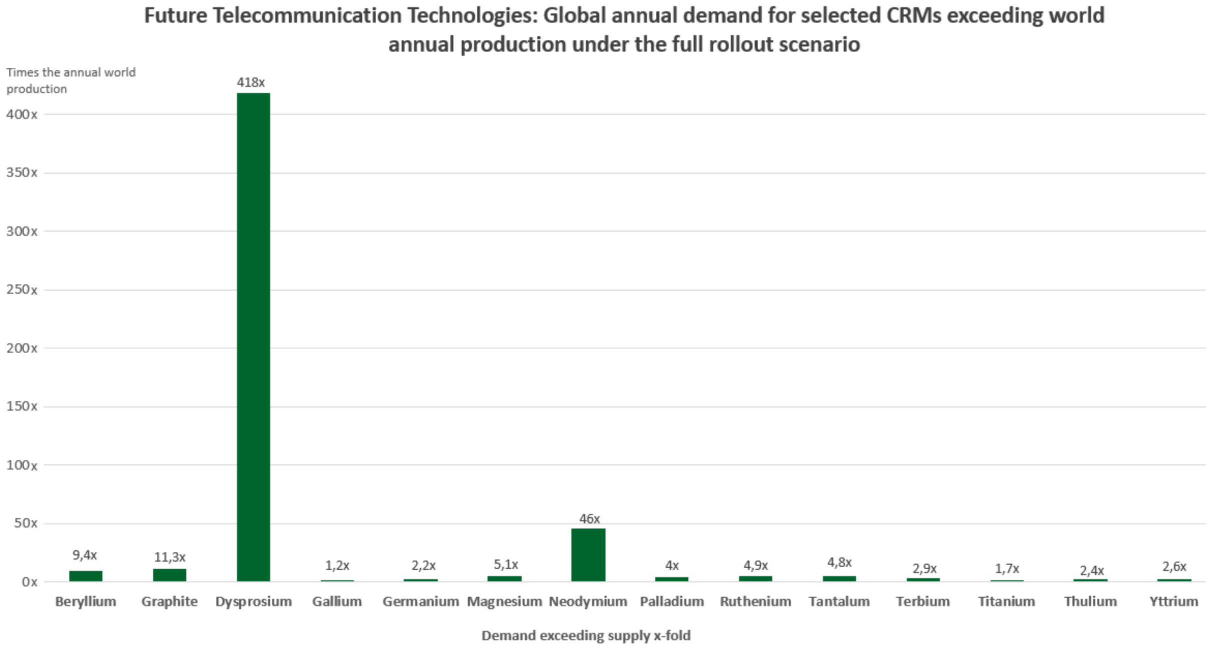


Figure 6.19: Future Telecommunication Technologies: Global demand of CRMs exceeding world annual production under a full rollout scenario.

In the case that all future telecommunication technologies would be globally rolled out, the demand of 14 CRMs would exceed the current annual world production rates. There is a big range in how much they exceed the supply: From 1,2-fold for Ga to 418-fold for Dy.

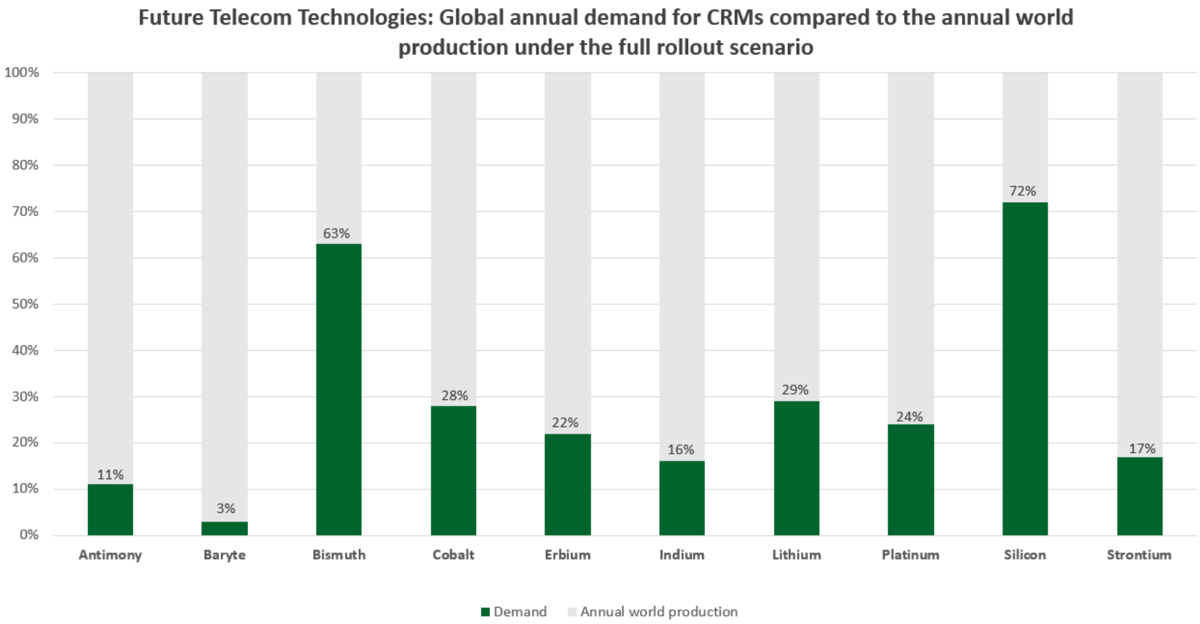


Figure 6.20: Future Telecommunication Technologies: Global demand of CRMs compared to world annual production under a full rollout scenario.

When looking at the remaining CRMs, quite high shares of supply would be required to meet the demand. This is especially the case for Bi with 63% of annual world production required and 72% for Si. However, also in the case of Co, Er, Li and Pt, between 22% - 29% would annually be required to meet the associated demand. For the remaining CRMs Sb, Ba, In and Sr, between 3% - 17% would be required.

Chapter 7: Creating Supply Chain Resilience for Critical Raw Materials

When the demand exceeds the supply, potential supply risks might threaten the available supply and thus cause bottlenecks. Thus, as part of the third research question *Which strategic choices do telecommunication companies have to secure supply chain resilience for Critical Raw Materials?*, focus was put on that. Creating supply chain resilience can be achieved by circular economy concepts that have the goal of decoupling resource consumption from economic activities by making waste valuable and improving material efficiencies (Ellen McArthur Foundation, 2020). The conducting of criticality assessments help to prioritize materials for circularity (Tercero Espinoza et al., 2020). Looking at the results of this study, the demand for Be, Graphite, Dy, Ga, Ge, Nd, Mg, Pd, Ru, Ta, Tb, Ti, Tm and Y exceeds current supply. In the following, different circular economy strategies will be mentioned that can have an impact on achieving resilient supply chains for telecommunication companies, as well as for other sectors.

Eco-design principles

The decision on design choices regarding CRMs for technologies is taken long before realizing products, but during the scientific research on the development of the technology (Babbitt et al., 2021; Peck et al., 2015). Looking through the design perspective, this technology research stage is the earliest point to reduce risks from material criticality, since later material changes are more difficult to exert (Babbitt et al., 2021; Collingridge, 1982). During the technology development, main emphasis is put on enhancing the technical performance and not designing for the EOL (Babbitt et al., 2021). Furthermore, it is also difficult to predict the exact use of the technologies, resulting in later risks (Babbitt et al., 2021; Collingridge, 1982). This was mentioned as part of interviews with experts. When looking at Quantum Senders and Quantum Receivers, a vast variety of different raw materials are contained in Cryocoolers. Amongst these are Ag, Au, Be, Cu, CuSn, Dy, Er, ErNi, ErNiCu, GaP, Ge, Graphite, GOS, H, Ho, HoCu, Mo, Nb, Steel, Pb, Pb replacement, Plastics, Pr, Natural Rubber, Re, Si and W, as gathered from different Quantum experts. After consulting Quantum Communication Expert A (2021), it became clear that it would be possible to exclude Cryocoolers from Quantum devices, however this would make the signal that is sent less clear and since telecommunication companies would require the best possible signal, until now it was no option to exclude Cryocoolers. Concluding from this, there should be eco-design principles for early stage technology development already, which includes research institutes that are aware of the topic and telecommunication companies that do not prioritize technical performance over material criticality. This should be strategically considered when developing new technologies and equipment types.

When looking at a later stage, exemplarily in the case of 5G Technologies, Edge Computing Servers or Photonics devices, some of the products were already introduced into the market. Following the state of the art, it is not business practice that product designers are especially putting emphasis on designing products for a better EOL (Norman, 1998). Focus is not put on material criticality, but rather on costs, market needs, corporate strategies or economic and scientific innovations (Ashby et al., 2013; Babbitt et al., 2021; Ashby et al., 2012). Focusing on the design for the technologies, there are challenges in the form of complexities of product compositions, small quantities of materials contained, difficulties separating components, as well as transparency on actual CRMs contained (Babbitt et al., 2021; Wang et al., 2014). There is a need within the design of new technologies to include product life extension strategies, as discussed in the following.

Design for reduce, reuse, repair, refurbish & remanufacture: Increasing the lifespan of products can be done through designing technologies for reuse, repair, refurbishing or remanufacturing (Tercero Espinoza et al., 2020). Instead of dumping old equipment it is wise to repair it and reuse, refurbish and remanufacture as much as possible. This can be done through modularization, standardization and a design for disassembly (Hagelueken, 2014). After expert interviews with Photonics experts and Quantum Technology experts it became clear that both technologies aim at using the current in-place infrastructure instead of building a new one. This means that exemplarily in the case of Quantum devices, devices will just be placed at the network and will use the fiber optical network as the current state of the art (Razavi, 2018). Contrary, in the case of 5G Technologies, the aim is rather to replace all 4G equipment by 5G Technologies (Personal Communication with KPN, 2021). As a mitigation strategy it can be mentioned that focus should be put on these design principles already at the early technology development stage.

Durability: Durability refers to a strategy of making technologies physically as well as emotional durable (Babbitt et al., 2021; Den Hollander et al., 2013; Chapman, 2005). In the case of physical durability, this means that technologies are built in a way that they are resisting fatigue or degradation (Den Hollander et al., 2013) by using robust high-quality lower level components (Babbitt et al., 2021). In theory, this leads to less demand for CRMs in the future due to keeping a stable economic value reflected through higher prices (Babbitt et al., 2021; Mccarthy et al., 2018). In the case of the emotional durability, emphasis is put on consumer behavior and their trust in and emotional attachment (Babbitt et al., 2021; Chapman, 2005; Bocken et al., 2016; Kasulaitis et al., 2020; Lobos et al., 2013). In the case of telecommunication companies, physical durability would be a good strategy for discussion with suppliers and research institutes for aiming for durability for every single lower level component of the future technologies. This can especially be crucial for 5G Technologies, which equipment is placed in locations where weather events can cause damage. However also the other technologies need some sort of strength to perform properly over a longer lifetime. Goal should be already in the technology development stage to target durability. Looking at the emotional durability, this can rather be neglected as part of future telecommunication technologies.

Dematerialization: This strategy includes reducing the amount of materials used within the technologies as much as possible to become material efficient (Babbitt et al., 2021). Telecommunication companies do only have quite limited influence on this strategy, since OEMs are manufacturing devices. However, there should be an open exchange between telecommunication companies and different stakeholders in order to achieve dematerialization while also maintaining high quality standards. This can be achieved by reducing the amounts of materials used per device or the amount of devices required. Also the above mentioned miniaturization and standardization can play a major role.

Recycling: One crucial strategy for material criticality, as well as circularity perspective is recycling (Tercero Espinoza et al., 2020). Recycling has the potential of increasing the independence of supply and can be a valuable additive to primary sourcing (Tercero Espinoza et al., 2020). Some CRMs are solely sourced as by-products to other materials mined and thus the dependence consists on the host metals (Tercero Espinoza et al., 2020). The below global-average EOL recycling rates for the identified problematic CRMs could be retrieved from the International Resource Panel (2011) and Matos et al. (2020).

Table 7.1: Average global end-of-life recycling rates for the problematic CRMs.

Problematic CRMs	EOL Recycling Rate	Source
Be	<1%	International Resource Panel (2011)
Graphite C	10%	Matos et al. (2020)
Dy	<1%	International Resource Panel (2011)
Ga	<1%	
Ge	<1%	
Nd	<1%	
Mg	> 25 – 50%	
Pd	>50%	
Ru	> 10 – 25%	
Ta	<1%	
Tb	<1%	
Ti	>50%	
Tm	<1%	
Y	<1%	

For those CRMs where demand is exceeding current supply, rather small recycling rates could be identified. Furthermore, Tercero Espinoza et al. (2020) discusses some major drawbacks arising from recycling CRMs: It is not always economic viable to recycle CRMs; collection rates and channeling of EOL scrap is challenging; thermodynamic incomparability for some metals (International Resource Panel, 2013); losing of some materials over the recycling of others; the use of small CRM volumes makes recycling harder. Looking at these dilemmas, there is an urgent need for telecommunication companies to foster more recycling activities. The knowledge on properly recycling CRMs lays at the downstream supply chain partners of telecommunication companies. In order to increase recycling rates, telecommunication companies could lobby for more recycling within their own network and with external stakeholders. Furthermore, investments into recycling technologies could trigger faster developments in recycling technologies and thus a faster recovery of CRMs and more secondary supply. Lastly, incentives need to be given for making it valuable for downstream partners to recycle CRMs that might not be economically viable. Telecommunication companies could start such incentive programs to increase recovery rates.

Substitution: Selecting the right materials is a crucial step in the technological development of future technologies. If one material is critical, there is the possibility to substitute it with other materials that can achieve the same or similar technical performances. However, this is very difficult and sometimes impossible for CRMs due to their physical and chemical properties, that are required for high performance applications (Babbitt et al., 2021). Problematic is also that for some CRMs, solely other CRMs exist as substitutes, such as for PGMs (Babbitt et al., 2021; Graedel et al., 2014; Llody et al., 2012). Exemplarily, for CRMs the following substitutes could be identified:

- InP in laser diodes can be replaced by GaAs (USGS, 2021): However, Ga is also a CRM
- Ta in electronic capacitors can be replaced by Al, ceramics or Nb (USGS, 2021): Nb is also a CRMs, however Al and ceramics might be an option since they are non-CRMs
- Y in electronics or lasers cannot directly be substituted with other materials (USGS, 2021)

This problem should be investigated into, preferably already at research institutes, which are developing future technologies. Telecommunication companies are advised to discuss this issue with researchers to find solutions on how to minimize or better avoid CRMs. As a distinction also the changing of material properties should be considered (Sprecher et al., 2015). During the conducted interviews, it became clear that research institutes are focusing on different material routes depending on the applications. Exemplarily, during a discussion with Professor A for Photonics Integration (2020), it became clear that PICs need to be made from Si for data centers, but in other cases mostly InP is used. This shows that substitution needs to be identified for all different use cases and depending on the required material properties.

Conflict Minerals

Besides CRMs, also conflict minerals play an important role in the material selection. Conflict minerals are those minerals associated with negative social implications, such as severe violations like the financing of warfare from illegal mining (Young, 2018). Furthermore, conflict minerals are also associated with small-scale and artisanal mining activities, where labor standards and human rights standards are ignored (RMIS, 2019). These raw materials are referred to as “3TG”- Tin, Tantalum, Tungsten & Gold (Young, 2018). Due to the heavy use in the electronics industry, special focus is put on responsible sourcing practices by manufactures to develop standards and audits (Young, 2018). When looking at the conducted study, Ta and W demand exceeds current supply. Furthermore, also Au was often reported by the experts (In the epoxy of Photonic Transceivers; in the cryogenics of Quantum Senders and Quantum Receivers), however was excluded since Ag is not a CRM according to the CRMs list of the European Commission (2020b). This shows, that it is required to be aware of this topic when working on the development of future technologies. Responsible sourcing practices need to be prioritized and conflict minerals excluded if no transparency exists for the supply chain. Thus, it is advised that telecommunication companies make responsible sourcing a requirement from their suppliers and they should lobby for the implementation of environmental and social standards for global value chains at the governmental level and also at research institutes they are working with.

Supply Diversification Strategies

Geographic Diversification: One strategy companies could choose is to geographically diversify mining and refining activities of their suppliers or increase the number of suppliers for lower level components and thus create resilience (Babbitt et al., 2021; Alonso et al., 2007; Griffin et al., 2019). When looking at the CRMs where demand exceeds supply, the following countries as main supplying countries could be identified:

Table 7.2: Overview on main supplying countries of most problematic CRMs (European Commission, 2020b).

Problematic CRMs	**Main global supplier**
Be	United States (88%)
Graphite C	China (69%)
Dy	China (86%)
Ga	China (80%)
Ge	China (80%)
Nd	China (86%)
Mg	China (89%)
Pd	Russia (40%)
Ru	South Africa (93%)
Ta	Democratic Republic Congo (33%)
Tb	China (86%)
Ti	China (45%)
Tm	China (86%)

Y	China (86%)

China represents the main supplying countries. Looking at Dy and Nd, where demand exceptionally exceeds supply, around 90% of supply is coming from China. And also for the other CRMs, very high geographical concentrations can be identified within just one country. This shows, that a supply diversification strategy is recommended for the four future telecommunication technologies in order to have a resilient supply also in the case that geopolitical aspects play a role between different nations. Even though telecommunication companies do not have a direct influence on the decision on where to source raw materials, they can still serve as an enabler for a dialogue about it with first tier suppliers.

Ownership-based Diversification: Another strategy for diversification can be based on the ownership of mines or supply chain stages domestically and in other countries (Patrahau et al., 2020; Sprecher et al., 2015). This means that solely sourcing from other parts of the world, does not necessarily make a company independent from a supplying country, such as China (Patrahau et al., 2020). A strategy for this can be to invest into local mining and processing (Patrahau et al., 2020). Even though this is an immense costly and often political decision, telecommunication companies could lobby for that at a governmental level in order to highlight problems they are facing for their future technologies and that a secured supply is crucial for the European economy. Having a stable communication infrastructure is extremely crucial for every single industry as well as society and will guarantee that Europe stays competitive compared to other continents. Drawbacks are that exemplarily in the case of RRE, such as Dy and Nd, it can take 6-10 years from exploration to mining (Patrahau et al., 2020; De Boer et al., NA). This shows that time constraints might make local sourcing problematic.

Stockpiling: One strategy for companies would be to stockpile raw materials. This strategy aims at securing supply by accumulating important CRMs and thus make companies less exposed to possibly occurring restrictions in supply (Patrahau et al., 2020; Sprecher et al., 2015). This would result in resilience since stocks could be build up and price fluctuations would not have impacts on a company's supply chain (Patrahau et al., 2020). However, firstly choosing this strategy would only relief pressure on supply chains in a short term and would not solve the issue of material criticality. Thus, circular economy principles should be preferred. Secondly, telecommunication companies are service providers and do thus solely purchase equipment from OEMs and not manufacture any equipment themselves. This means that there is only indirect influence telecommunication companies can have on a stockpiling strategy. Thirdly, if stocks of raw materials are heavily aggregated for whole industries, this also influences the market through market demand surges or price increases (Patrahau et al., 2020; Sprecher et al., 2015), leading to a rebound effect.

Cross-chain collaboration

There are three different kinds of strategic corporate alliances, that have the potential for capacity building and knowledge exchange: Firstly, collaboration between stakeholders of same sector companies between countries in order to make agreements on the exchange of resources, as well as capabilities (Patrahau et al., 2020; Canzaniello et al., NA). According to Patrahau et al. (2020) this is important, because CRM intense sectors are privatized and do have to act for ensuring their own supply. For telecommunication companies, a horizontal alliance is recommended, because same issues are faced. By forming alliances, a higher bargaining power can be achieved, which can be used for lobbying for the topic of material criticality with stakeholders. Secondly, collaboration also needs to be achieved across the whole value chain (Patrahau et al., 2020). Telecommunication companies should collaborate upstream and downstream in order to share resources and achieve value (Patrahau et al., 2020; Baojun et al., 2019). Thirdly, it is also crucial to include external stakeholders, such as consumers, academia, non-governmental organizations or policymakers to grasp the full range of involved actors.

Examples for international organizations supporting sustainable sourcing practices are the Fair Cobalt Alliance, International Council on Mining & Metals, Initiative for Responsible Mining Assurance or Responsible Minerals Foundation (IEA, 2021). Telecommunication companies do have the option of supporting these organizations.

Redesign for Circular Business Models

One of the strategies that can be chosen is to look at the telecommunication companies and their OEM's business models and to redesign it according to circular economy principles. There is a vast variety of different circular business models, that were summarized by Lewandowski (2015) and include exemplarily: Product lease, where the product is given as a service and the ownership stays with the manufacturer (Tukker, 2004) or also solely using circular supplies and recycled or bio-based materials (Lacy et al., 2014).

Different strategies could be chosen for telecommunication companies. Together with Supplier B for 5G Technologies (2021) a rethinking on the business model was discussed. Looking at the current state of the art, suppliers develop and produce electronic components used in telecommunication equipment. Depending on the suppliers, either specific applications are developed or new (component) technologies can be developed. This equipment will then be sold to the telecommunication service provider, which at the EOL has the responsibility for dealing with the waste. A more circular business model could however be, that the tier 1 suppliers do just rent out the function of the equipment. Exemplarily, a 5G Antenna could just be rented out to the telecom service provider. This would mean, that the tier 1 supplier could contribute directly to the product development through eco-design principles or predictive maintenance with the goal of balancing the actual use with its lifetime, energy and material efficiency. This concept would be a product-as-a-service model, with the ownership of the product staying with the tier 1 supplier, resulting in the responsibility for dealing with the product at the EOL. Thus, the supplier could foster recycling, or re-deployment elsewhere. Additionally, recycling would be more efficient, due to large quantities of the same product. Lastly, also the CRMs would still belong to the supplier.

Another different business model could be to apply a sharing economy to own operations. This means that the fixed network, like 5G base stations could also be shared with other telecommunication providers, leading to smaller investment costs and less negative environmental implications (Telia Company et al., 2021).

Lobbying and investment for new mining activities

Urban Mining: An emerging field in research is to recover materials located in urban regions (Krook et al., 2011; Brunner et al., 2004). These materials are part of supply systems, such as telecommunications or power and water infrastructure (Krook et al., 2011; Gerst et al., 2008; UNEP,

2010) and often have not been collected as part of disposal management (Krook et al., 2011; Bergbäck et al., 2001; Hedbrant, 2003). Aggregations of obsolete materials can be found in urban environments, which are often not identified due to a lack of knowledge on the occurrence and amounts (Krook et al., 2011). Recovering materials from such so-called "hibernating stocks" could be a valuable additional strategy, telecommunication companies could choose. Telecommunication systems are spread widely across urban, sub-urban and non-urban region and it is likely that over time, some of those stocks were forgotten and new stock was build up. Thus, telecommunication companies should work together with different stakeholders for identifying these stocks and foster the recovery, followed by recycling or reuse to give materials a second life.

Deep-sea mining: Even though telecommunication companies have only very little influence on deep-sea mining, it is necessary to mention that exploration operations are happening in some parts of the world. According to the IEA (2021), below 200m in the ocean, the crust could be mined to access CRMs such as Co, Pt, REEs or Ba. Exemplarily in the Pacific Ocean it is expected to find 44Mt of Co (IEA, 2021; Hefferman, 2019). However, there are still environmental, economic and technical concerns associated with deep-sea mining, before risks are fully understood (IEA, 2021). Amongst such negative implications are disturbance of the seafloor, ocean pollution, destruction of ecosystems and possible negative impacts on biodiversity (IEA, 2021). According to Hefferman (2019), testing sites did not recover from exploration plans for more than 30 years. Thus, lobbying for this approach could be a geographical diversification strategy in the long term, however before risks are not fully understood and arising negative implications are fully excluded, it is not advised to further include this option into the companies material strategy.

Chapter 8: Discussion

The following sub-chapters include the interpretation of the results of the study, limitations and recommendations for future research.

8.1. The Interpretation of the Results

CRM frequency of occurrence and associated supply risks

When looking at the general findings, for all future technologies together, a very broad range of different CRMs could be identified. The highest variety is contained in 5G Technologies, followed by Photonics, Edge Computing and lastly Quantum Technologies. The highest occurring CRMs across the four technologies are Si, Ti, Ga, P, Ge and Er. Amongst them Er has the highest supply risks. This large variety of different CRMs and high occurrence and supply risks of CRMs in all four technologies pose negative implications on the further development and rollout of the technologies and those on the telecommunication industry. In the case that out of the CRMs with the highest occurrence, even one CRM cannot be accessed, all four technologies are at risk. If all four technologies are at risk, the future of the telecommunication industry is at stake.

Demand increase and supply comparison

It can be expected that the demand for CRMs contained in the four telecommunication technologies will rise 8-fold to 15-fold under the slow and fast rollout scenarios until 2030 and 16-fold under a full rollout scenario. The highest CRM demand comes by far from 5G Technologies. When aggregating all CRMs contained in all four future technologies, the six largest CRMs in quantity are from the biggest to the lowest Natural Graphite, Si, Mg, Ti, Nd and Ba. This means that telecommunication companies need to be aware of this demand increase in the future and the importance 5G Technologies have in their strategic portfolio of technologies. Additionally, when looking at the supply side, specifically 14 CRMs could be identified which demand will exceed the current world annual production rates in one of the scenarios: Be, Natural Graphite C, Dy, Ga, Ge, Mg, Nd, Pd, Ru, Ta, Tb, Ti, Th and Y. This is highly problematic, since access to these CRMs cannot be secured in the future when looking at current supply levels. This means, that it is highly important for telecommunication companies to focus on how they can decrease demand already now, as well as find additional sources for supply in order to mitigate arising bottlenecks in the future.

Besides the demand from the telecommunication sector, demand will also arise from sectors, such as the transportation and the energy sector. Especially the CRMs Dy, Nd, Pd, Ru, Si, Tb, Tm and Y are present in all three different sectors. Comparing those total numbers, a higher mineral demand is arising from the transportation and energy sector, than from the telecommunication sector, however the increase is expected to be higher throughout the years for the telecommunication sector. For the energy and transportation sector, highest increase per CRM is arising from Li (42-fold), followed by Graphite (25-fold), Co (17-fold) and REEs (7-fold). In the case of REEs, depending on the scenarios, a higher demand increase was identified for individual CRMs, such as Dy, Nd, Tb and Y for the telecommunication industry.

Looking at these findings, a clear problem is arising. This problem is that not only the telecommunication sector will require huge amounts of CRMs, but also from other sector's demand increases are expected. When summing up demand increase, hypothetically Li will not just require a 42-fold increase, but adding up a full rollout scenario hypothetically will result in a 51-fold increase. This demand increase can result in higher supply risks globally, because more resources will be required through more globally spanned untransparent supply chains, requiring even more geopolitical diplomacy, resulting in negative social and environmental implications and are threatened through price volatilities or market changes.

Furthermore, there are additional problems to that: Firstly, we require a clean energy transition, because of the very urgent need to reduce GHG emissions globally. If emissions cannot be reduced in a very fast pace, humanity will exceed tipping points, leading to unreturnable natural catastrophes. Secondly, also the telecommunication sector is of crucial importance to basically all other sectors since it provides the digital infrastructure for all other sectors to function. This means that the energy sector and the transportation sector will not function without the underlying telecommunication sector. Lastly, CRM issues might be able to be solved by all different strategies, however the constraints of timing related to the destruction of the planet makes the matter very urgent. Thus, finding a solution to this problem is very complex and it is questionable, if a real solution can be found or whether compromises need to be made for every part of a solution.

Additionally, another constraint is arising. Until now 5G Technologies are seen as the most important technology of the four with telecommunication companies focusing on it within their strategies. However in order to use 5G Technologies to its highest benefit, Photonics is required to provide a fast connection and Edge Computing to process the amount of required data. Furthermore, regarding the research findings, it could be identified that 5G Technologies also require the largest variety of CRMs, as well as the highest demand. This puts additional pressure on the situation. The result of this is that future technologies might also compete with each other for resources.

Supply Chain Resilience strategies

Supply risks mitigating strategies included the design of technologies after eco-design principles, increase recycling rates, investigate into substitution potential, diversity supply geographically as well as ownership based, avoid conflict minerals by responsible sourcing, stockpiling, lobbying for new mining activities, foster cross-chain collaboration and redesign whole business models after circular economy principles. All of these strategies are strongly advised to be checked on whether they can be implemented at the company level.

By implementing these strategies at a company level, supply chain resilience can be achieved, resulting in less exposure to supply risks for CRMs. By reducing the amount of CRMs, shifting away from CRMs or securing access to more CRMs, telecommunication companies have an opportunity of ensuring that their future technologies will be able to be rolled out. Rolling out these technologies are crucial for corporate strategies and thus the future of the telecommunication industry. However, the fact that resources will still be heavily consumed should not be neglected. Even if we would implement these supply chain resilience strategies, this might positively influence the companies strategies and buys time in order to fight climate change through low carbon technologies but looking through a holistic perspective, negative implications will still not just disappear. Thus, it is crucial to mention that it should be seriously considered to reflect on whether all of these technologies do really bring a positive benefit to society and the environment.

8.2. Limitations of chosen Research Approach

There are several limitations that needs to be mentioned. The following sub-chapters give explanations on them.

8.2.1. Critical Raw Material Identification

EU CRM list: For the scope of this study and to define CRMs, the list of the European Commission (2020b) was taken as a basis. However, the this list represents criticality through the lenses of the EU economy. This means that the CRMs are defined through their economic importance to the EU economy, as well as associated supply risks. However, when looking through the perspective of a telecom service provider, different CRMs might be critical. Thus, in order to draw more detailed conclusions, a company-level, technology-level or even product-level criticality assessment to define CRMs would have been necessary.

Furthermore, the European Commission (2020b) CRM list used represents the year of 2020. However, the whole purpose of this study was to look into the future. Thus, it would have been necessary to not just define which CRMs are critical as of 2020, but rather which might become critical in the future and which others might not be critical anymore (like e.g. today’s non-critical H). However, this was outside the scope of this study.

Equipment selection: Looking at the equipment selected, there are strong differences between the four technologies. For Quantum Technologies and Photonics, three devices could have been identified, while for Edge Computing data could only be gathered for one device. In the case of 5G

Technologies, several anonymized equipment of whole networks was reported. Identifying different CRMs contained in those equipment types is thus biased, since there can be more CRMs contained, if simply more equipment was selected. This results in difficulties drawing conclusions for the whole technologies based on the selected devices. Furthermore, also comparing the different technologies might be difficult.

Additionally, one limitation that needs to be mentioned is that the selected equipment types were based on data availability. Furthermore, the identified CRMs are thus also based on data availability. This equipment of the different technologies however only represents a snapshot of the whole impact of the technology on the world. Exemplarily, for 5G Technologies, CRMs were identified for the RAN and the Mobile Network. However, that the reach of 5G Technologies is much broader, such as companies employing their own 5G Networks at production sites or smart devices in the daily life of people (e.g. drones, robots, etc.), was not part of the study. However, this also needs to be investigated into for identifying the whole impact of 5G Technologies.

CRM Data Gathering: The whole data gathering process was very extensive and time consuming and for some technologies more difficult than for others. A reason for that was that often data was not readily available and thus firstly needed to be discussed internally and identified. In general, it was identified that for technologies that are going to be implemented at a later point in time, it was easier to gather data than for technologies that are already in place. Additionally, gathering data from research institutes was in general easier than gathering data from suppliers due to data sharing restrictions. Due to the fact that data was not readily available and needed to be gathered in some cases approximately from different parties, there might be a discrepancy in the data that was really reported.

Additionally, it cannot be entirely concluded that the reported CRMs also represent all CRMs that are included in the devices. Exemplarily, for some Quantum Devices, CRMs contained in electronics were excluded when data was shared, due to a lack of knowledge. However, especially in the case of electronics, a variety of CRMs occur.

Furthermore, in a lot of cases CRMs and other raw materials were reported, which however consisted of alloys. In the case of alloys, the approach chosen was, in case GaAs was included, to just count Ga as a CRM. This might not entirely picture the reality but is acceptable as part of this research. However, in the case of exemplarily steel or Al, this is problematic. Al alloys always consist of CRMs in very low concentrations making it hard to recognize that they are contained (Arowosola et al., 2019). To mention another example, in the case of high-performance steel in exemplarily industrial equipment, CRMs such as Nb, V or other CRMs are used to achieve the required strength (Babbitt et al., 2021; Kuziak et al., 2008; Béres et al., 2004). As part of this study, Al and steel was excluded due to not being CRMs according to the European Commission's (2020b) list on CRMs. However, this is clearly a limitation of the study, since it neglects some CRMs contained as well as their quantities.

Lastly, it needs to be mentioned that the conclusions of this study and the findings are based on a case study conducted with a Dutch telecommunication service provider. These could potentially change in case the study would focus on another case study within the telecommunication industry.

Technological Routes: Generally, especially electronics are evolving very fast over time with main trends, such as devices becoming smarter, multifunctional or smaller in size (Peck et al., 2020). This study focuses on the current state of technology development. Thus, it solely includes CRMs that are currently expected to be used or different CRMs that are currently researched on. In some cases, CRMs that would actually substitute each other within the technology are both included to have a full overview on possible CRMs contained in the equipment. Exemplarily in the case for Quantum Technologies, if one CRM is used for the manufacturing of a device, another CRM is not used. According to Expert A for Quantum Communication (2021), there are a lot of interdependencies in the CRMs data, such as that in case that Molybdenum is used for the manufacturing of a Quantum Receiver, Tungsten will not be used. Thus, counting both weights would bias the results and put an overweight on the used CRM (even though this is not the case here, since Molybdenum is not a CRM according to EU's definition of CRMs (2020)). Unfortunately, due to a lack of technical knowledge it was not possible to properly map those interdependencies. Furthermore, during the CRM data gathering process, often a brainstorming on potential CRMs contained in devices with the technology experts took place, where interdependencies were neglected. This limitation should be kept in mind when looking at the results. Moreover, over time, due to marketing and innovation activities of companies, a pull is created for different materials, which would make the technologies perform in a way, the market is demanding it (Peck et al., 2020). However, these developments were out of the scope of this study. Additionally, it was also excluded that the equipment might change and lower level components might be excluded and new ones included in order to change its purpose.

Occurrence x Supply Risk Assessment: In order to identify which CRMs are occurring in which frequency and which supply risks are associated with them, the occurrence and supply risk assessment was conducted. However, again as discussed above, supply risks are through the lenses of the European Union's perspective and do not necessarily directly represent the risks telecommunication companies are facing. Additionally, telecommunication companies mainly source components and not raw materials and thus the supply risks would depend on the manufacturers of components.

8.2.2. Demand Scenario Development and Supply Comparison

CRM Weights Data Availability: When looking at the weights data gathered, it can be concluded that except for some 5G Technology devices and the Photonics Amplifier, all other equipment types that were defined before could be included into the demand scenario developments. Even though this is a good quote, for giving a full picture on the findings, information would needed to be gathered for the remaining equipment as well. This also plays a role in the discussion of the occurrence of different CRMs related to the demand exceeding supply, since not all CRMs weights that were reported to be contained in future technologies were also part of the CRM demand calculations.

Demand Scenario Development: In order to develop the demand scenarios, it was assumed that the demand develops according to specific, based on a literature review, defined growth rates until before defined timeframes of 2030 for 5G Technologies, Photonics and Edge Computing, as well as 2050 for Quantum Technologies. Thus, the calculation was simply based on multiplying amounts of materials times the expected device amounts throughout the years. However, for making more precise scenarios, other variables would have needed to be taken into account. The demand does not necessarily scale up linearly, but also depend on the diffusion of the products in the market and which functionalities consumers are demanding, since those functionalities are dependent on the material developments (Peck et al., 2020). Thus, the material demand would be influenced by that. Secondly, scenarios also depend on the lifetime of the products, for the lower level components as well as the whole products and technologies, which in return influences the demand for the materials used (Peck et al., 2020). If the lifetime of products can be extended, less new CRMs would be required. The same also holds true in case it is possible to reuse components or devices. Furthermore, also externalities, such as political developments impacting slower or faster rollouts of technologies can impact the demand. Exemplarily, policy makers investing more into digitalization might trigger stronger demand even faster. Lastly, organizations also become more aware of the issue around CRMs and this can also have an influence on the demand.

The third developed scenario was the hypothetical calculations of a full rollout scenario. Since it is quite difficult to estimate amount of devices globally, calculations were based on assumptions and available data from market research institutes. This however might have the drawback that depending on assumptions outcomes might vary. In this case, assumptions were often based on either global settlement area, global fiber coverage or global shipment of servers. However, taking other underlying variables might lead to a different result. In the case of Quantum Technologies, the fast rollout scenario was also taken for a full rollout scenario until 2050, because other data was impossible to retrieve and this approach was proposed by Quantum Communication experts.

Snapshot in time: The biggest constraint of the demand and supply comparison is that the supply numbers were taken as current annual world production rates. Thus, the forecasted supply was compared to the situation as of today. However, this neglects the fact that there might be more mining activities in the future or new deposits explored. Thus, to make conclusions more precise, it would have been necessary to take supply forecasts and compare predicted supply with demand. However, this is very difficult to do, since exemplarily for Quantum Technologies, forecasted supply by 2050 would have needed to be compared.

8.2.3. Supply Chain Resilience Strategies

Circular Economy Strategies: As part of the identified strategies, main emphasis was put on circular economy strategies that can mitigate criticality. Included literature was solely focusing on this as well. However, when looking through a corporate perspective of telecommunication companies, there might be additional strategies that could be chosen, which have a more business approach. However, these were outside the scope of this study.

Generalizing: Another limitation of the selected strategies is that this research just generalized strategies that could be applied for all CRMs. However, the reason for criticality is quite various. Thus, depending on the CRM or the component and technology it is contained in, different supply chain resilience strategies should be chosen. However, going into this much detail was also outside the scope of this study.

8.3. Recommendations for further Research

Criticality Assessment: One of the limitations of this study is that the underlying CRM list used is the one through the perspective of the European Union. Thus, it is recommended to conduct a criticality assessment from the perspective of a telecommunication company or the future technologies. This would potentially lead to different conclusions for the raw materials considered to be *critical*. However, this would not have an impact on the future material demand and supply comparison.

Research on other equipment and technologies: One recommendation for future research is to conduct a more in-depth analysis on different equipment for the four technologies and to include different technological routes they might take. Each of the selected technologies does have additional equipment that might also vary according to the models and the suppliers, as well as that changes over time depending on use cases and material advancements. Additionally, solely four future technologies were selected, but there will also be other future technologies that will require investigation. Exemplarily, these include Energy Harvesting, Serverless, Hyper automation, Open source, Human-AI interaction or the Semantic Web (KPN, 2020). Hence, in order to draw clearer conclusions on the associated demand for the whole telecommunication industry, such analysis would need to be conducted.

Scenario Development: Another recommendation for the scenario development includes the development of scenarios that take other aspects into account, such as technological changes from consumer requirements, the lifetime of products or political developments. This would give the whole future demand another perspective and it would be interesting to see how the demand would look like under other scenarios.

Demand from other sectors: As part of this research, the demand from future telecommunication technologies were solely compared with the material demand from the transportation and energy sector. However, other sectors will require CRMs as well. Thus, it is recommended to conduct a more in-depth comparison with other sectors that will also require amounts of CRMs.

Supply Development: The scope of this study solely included putting the future demand for CRMs in the perspective of current supply. However, it is recommended to conduct this study all few years to incorporate changes in the supply. Alternatively, forecasts of supply should also be considered for a comparison with forecasted demand.

Finding a solution to the problem: Furthermore, it is recommended to develop a strategic roadmap for the telecommunication industry for securing supply chain resilience within their supply chains. Telecom companies are in a unique position of being an enabler for the collaboration between different supply chain partners. This position needs to be used fruitfully for finding a systemic solution for material criticality. Finding such a systemic solution includes changes along the value chain, as well as along the life cycle of products and through the external framework of policy options. Within this field of tension, telecommunication companies need to find the best possible corporate strategy.

Chapter 9: Conclusion

A digital transformation comes with future telecommunication technologies. These future technologies have the potential of enabling sustainable use cases, such as remote healthcare or improvements in air quality and emission monitoring. The future network equipment consists of a variety of raw materials. Some of these raw materials are considered to be *critical*. Material criticality is defined by its supply risks that might constrain the implementation of future network equipment.

In order to mitigate those supply risks, telecommunication companies need to create resilience within their supply risks. Thus, the main research question of this research was *Which strategic choices do telecommunication companies have to secure supply chain resilience for Critical Raw Materials contained in future technologies?* In order to answer this, firstly CRMs for future technologies were defined, their bottlenecks were identified and based on that strategic choices could be given.

The first phase of this research included the identification of CRMs contained in future telecommunication technologies. The selected future technologies were 5G Technologies, Photonics, Edge Computing and Quantum Technologies. When looking at the general findings, for all future technologies together, a very broad range of different CRMs could be identified. The highest variety is contained in 5G Technologies, followed by Photonics, Edge Computing and lastly Quantum Technologies. The highest occurring CRMs across the four technologies are Si, Ti, Ga, P, Ge and Er. Amongst them Er has the highest supply risks. Also Dy and Nd, contained in three out of four technologies do have very high supply risks.

Following the CRM demand scenarios, it can be expected that the demand for CRMs will rise 8-fold to 15-fold under the slow and fast rollout scenarios until 2030 and 16-fold under a full rollout scenario. The highest CRM demand comes by far from 5G Technologies. When comparing the future demand with current supply, specifically 14 CRMs could be identified where demand exceeds supply: Be, Natural Graphite C, Dy, Ga, Ge, Mg, Nd, Pd, Ru, Ta, Tb, Ti, Th and Y.

The following Table 9.1 gives an overview on the summarized research findings and brings together occurrence, supply risks and the demand and supply comparison.

Table 9.1: Summary of the study findings

CRM	Occurrence in x out of 4 technologies	In following technologies contained	Supply Risks according to the EU from 1 to 7	Future demand exceeding current supply under slow rollout by x-fold	Future demand exceeding current supply under fast rollout by x-fold	Future demand exceeding current supply under full rollout by x-fold
Be	2	5G, Q	2,3	4,6	9	9,4
C	2	5G, Q	2,3	5,5	10,9	11,3
Dy	3	5G, EC, Q	6,2	92	161	418
Ga	4	5G, P, EC, Q	1,3	0	0	1,2
Ge	4	5G, P, EC, Q	3,9	0	1,9	2,2
Nd	2	5G, EC	6,1	10,2	17,8	46
Mg	3	5G, P, EC	3,9	2,5	4,9	5,1
Pd	3	5G, P, EC	1,3	1,9	3,8	4
Ru	2	5G, EC	3,4	1,8	3,5	4,9
Ta	3	5G, P, EC	1,4	1,3	2,3	4,8
Tb	1	5G	5,5	1,4	2,8	2,9
Ti	4	5G, P, EC, Q	1,3	0	1,6	1,7
Tm	1	5G	6,1	0	2,2	2,4
Y	1	5G	4,2	1,3	2,5	2,6

5G = 5G Technologies; P = Photonics; EC = Edge Computing; Q = Quantum Technologies

Firstly, when looking at the 14 CRMs where demand exceeds supply, the CRMs Ga, Ge and Ti are also occurring in all four technologies and are thus relevant for all technologies. Furthermore all of the 14 CRMs are contained in 5G Technologies, while 9 are contained in Edge Computing and 6 in each Photonics and Quantum Technologies. This shows that basically CRMs will not be available in the future under current circumstances, impacting all technologies.

Secondly, when looking at these 14 CRMs through the supply risk perspective, especially the CRMs Dy, Nd, Tb and Tm are problematic. For both Tb and Tm, demand exceeds supply for at least the fast and full rollout scenarios in a range between 1,4-fold and 2,9-fold. This already poses a huge threat, however, when looking at the supply risks coming from Dy and Nd it can also be concluded that the future demand for those two CRMs will also heavily exceed current supply in a range of 10,2- fold to 418-fold depending on the scenario. This is very problematic, because these CRMs do not only occur in at least two out of the four technologies, but do also have very high supply risks and also do have a very high demand exceeding the current annual world production rates. Since it can be clearly concluded that the demand increase for those CRMs exceeds the current supply, while some CRMs are also frequently used in the different technologies and are associated with very high supply risks, a clear risk is imposed on the future rollout of these technologies. If supply cannot meet demand, technologies will not be able to be rolled out and company's strategies are at risk and thus the future of the telecommunication industry.

Thirdly, supply chain resilience is a way of contributing to a solution for material criticality. Supply risks mitigating strategies included the design of technologies after eco-design principles, increase recycling rates, investigate into substitution potential, diversity supply geographically as well as ownership based, avoid conflict minerals by responsible sourcing, stockpiling, lobbying for new mining activities, foster cross-chain collaboration and redesign whole business models after circular economy principles. All of these strategies can be strategic choices for telecommunication companies and are advised to be considered at the company level.

So far, not a lot of research had been conducted on identifying CRMs contained in future telecommunication technologies. Most research focuses on the energy and transportation sector. With this study, a meaningful contribution could be given to further explore the topic of CRMs in combination with the telecommunication sector. This sector is highly important for the digital transformation the world is currently undergoing and should thus be focused on.

Regarding future research, it is recommended to conduct a more detailed analysis on other equipment types of the selected technologies, incorporate potential technological routes they might take and add other future telecommunication technologies to paint an even clearer picture on future demand. Furthermore, it is recommended to develop scenarios that are not solely based on device development but are also influenced by potential customer preference changes or political regulations. Here, also demand from other sectors can play a role, which might compete with the telecommunication industry for resources. Thus, demand from other sectors, not just the energy and transportation sector, should be monitored. Another recommendation is to have a closer look at supply developments and forecasted supply and then compare it with the demand from future telecommunication technologies. Lastly, it is highly recommended that telecommunication companies work on supply chain resilience strategies and align them with their corporate strategies.

References

Achzet, B.; Helbig, C. (2013). How to evaluate raw material supply risks –An overview. Resources Policy, 435-447.http://dx.doi.org/10.1016/j.resourpol.2013.06.003.

Alonso, E., Gregory, J., Field, F., and Kirchain, R. (2007). Material availability and the supply chain: risks, effects, and responses. Environ. Sci. Technol. 41, 6649–6656.

Amiri, I. S.; Azzuhri, S. R. B; Jalil, M. A.; Hairi, H. M.; Ali, J; Bunruangses, M and Yupapin, P. (2018). Introduction to Photonics: Principles and the Most Recent Application of Microstructures. Micromachines, 9, 452, doi:10.3390/mi9090452.

Appas, F.; Baboux, F.; Amanti, M. I.; Lemaitre, A.; Boitier, F.; Diamanti, E. and Ducci, S. (2021). Flexible entanglement-based secure communication with an AlGaAs chip for quantum networks.

Arowosola, A.; Gaustad, G. (2019). Estimating increasing diversity and dissipative loss of critical metals in the aluminum automotive sector. Resour. Conserv. Recycl. 150, 104382.

Ashby, M.F. (2012). Materials and the Environment: Eco-Informed Material Choice (Butterworth-Heinmann). ISBN 9780123859716.

Ashby, M.F., and Johnson, K. (2013). Materials and Design: The Art and Science of Material Selection in Product Design (Butterworth-Heinemann). ISBN 978-0080982052.

Babbitt, C. W.; Althaf, S.; Cruz Rios, F.; Bilec, M. B. and Graedl, T. E. (2021). The role of design in circular economy solutions for critical materials. One Earth 4, https://doi.org/10.1016/j.oneear.2021.02.014

Baojun Yu, Hangjun Xu, and Feng Dong, "Vertical vs. Horizontal: How Strategic Alliance Type Influence Firm Performance?," Sustainability 11, no. 23, 3, https://doi.org/10.3390/su11236594.

Béres, M., Weirich, T.E., Hulka, K.; Mayer, J. (2004). TEM investigations of fine niobium precipitates in HSLA steel. Steel Res. Int. 75, 753–758.

Bergbäck, B., Johansson, K., Mohlander, U., (2001). Urban metal flows a case study of Stockholm. Water, Air and Soil Pollution 1, 3e24.

Bittencourt, L. F.; Lopes, M. M.; Petri, I.; Rana, O. F. (2015). Towards virtual machine migration in fog computing. Paper presented at the 10th international conference on P2P, parallel, grid, cloud and internet computing (3PGCIC), Krakow, 4–6 Nov 2015.

Bocken, N.M.P., de Pauw, I., Bakker, C., and van der Grinten, B. (2016). Product design and business model strategies for a circular economy. J. Ind. Prod. Eng. 33, 308–320.

Bonilla, S.H., H.R.O. Silva, M.T. da Silva, R.F. Gonçalves, and J.B. Sacomano (2018). Industry 4.0 and Sustainability Implications: A Scenario-Based Analysis of the Impacts and Challenges, Sustainability, Vol. 10, No. 10.

Bonomi, F.; Milito, R.; Zhu, J.; Addepalli; S. (2012). Fog computing and its role in the internet of things. Paper presented at the first edition of the MCC workshop on mobile cloud computing, Helsinki, 17 Aug 2012.

Brogi A.; Forti, S. (2017). QoS-aware deployment of IoT applications through the fog. IEEE Internet Things J, 4, 1185–1192.

Brunner, P.H., Rechberger, H. (2004). Practical Handbook of Material Flow Analysis. Boca Raton, Lewis Publishers. Energy Market Inspectorate, 2010.

Canzaniello, A.; Hartmann, E. and Fifka, M. S. “Intra-Industry Strategic Alliances for Managing Sustainability-Related Supplier Risks: Motivation and Outcome,” International. Retrieved from from Patrahau et al. (2020).

Ciacci, L.; Werner, L. L.; Vassura, I.; Passarini, F. (2019). Blacklighting the European Indium Recycling Potentials. Journal of Industrial Ecology, Vol. 23 (2), 2019, pp. 426-437.

Chapman, J. (2005). Emotionally Durable Design: Objects, Experiences (Earthscan Publications).

Collingridge, D. (1982). The Social Control of Technology (Open University Press).

de Boer and Lammertsma, “Scarcity of Rare Earth Elements,” 2049, Retrieved from Patrahau et al. (2020).

de Koning, A., Kleijn, R., Huppes, G., Sprecher, B., van Engelen, G., Tukker, A., (2018). Metal supply constraints for a low-carbon economy? Resour. Conserv. Recycl. 129, 202-208. https://doi.org/10.1016/j.resconrec.2017.10.040.

Deloitte (2019). Semiconductors – The Next Wave. Opportunities and winning strategies for semiconductor companies. Retrieved from deloitte-cn-tmt-semiconductors-the-next-wave-en-190422.pdf on 10th May 2021.

den Hollander, M.C., Bakker, C.A., and Hultink, E.J. (2017). Product design in a circular economy: development of a typology of key concepts and terms. J. Ind. Ecol. 21, 517–525.

Deutsche Rohstoffagentur (2016). Raw materials for emerging technologies 2016. ISSN: 2193-5319. Retrieved from https://www.deutsche-rohstoffagentur.de/DERA/DE/Downloads/zukunftstechnologien-zusammenfassung-en.pdf?__blob=publicationFile&v=5 on 12th October 2020.

Deutsche Rohstoffagentur (2021). Rohstoffe fuer Zukunftstechnologien 2021. Auftragsstudie. ISBN 978-3-948532-47-5.

Dianati, M.; Alleaume, R.; Gagnaire, M and Shen, X. (2008). Architecture and protocols of the future European quantum key distribution network. Security and Communications Networks. 1:57-74. DOI: 10.1002/sec.13.

Earth Magazine (2018). Mineral Resource of the Month: Cesium by U.S. Geological Survey. Retrieved from https://www.earthmagazine.org/article/mineral-resource-month-cesium/#:~:text=Mine%20production%2C%20consumption%2C%20import%20and,consumed%20in%20the%20United%20States on 28th May 2021.

Edison (2019). Zirconium and hafnium. Retrieved from https://www.edisongroup.com/edison-explains/zirconium-and-hafnium/#:~:text=Supply%20and%20demand%20data%20for,least%2075%25%20comes%20from%20China on 28th May 2021.

Elements Database (2015). Neodymium. Retrieved from http://www.elementsdatabase.com/Neodymium-Nd-60-element/#:~:text=Neodymium%20is%20mainly%20mined%20in,estimated%20at%20about%208%2C000%2C000%20tonnes. on 28th May 2021.

Ellen McArthur Foundation (2020). Concept. What is a circular economy? Retrieved from https://www.ellenmacarthurfoundation.org/circular-economy/concept on 30th December 2020.

Ericsson (2020). Ericsson Mobility Report. Retrieved from https://www.ericsson.com/4adc87/assets/local/mobility-report/documents/2020/november-2020-ericsson-mobility-report.pdf on 26th April 2021.

European Commission (2020a). Critical Raw Materials for Strategic Technologies and Sectors in the EU. A Foresight Study. doi: 10.2873/58081.

European Commission (2020b). Study on the EU's list of Critical Raw Materials (2020). Final Report. doi: 10.2873/11619.

European Commission (2020c). Building an ecosystem where IoT, edge and cloud converge towards a computing continuum. Retrieved from https://digital-strategy.ec.europa.eu/en/library/building-ecosystem-where-iot-edge-and-cloud-converge-towards-computing-continuum on 28th June 2021.

Florczyk, A. J.; Melchiorri, M.; Zeidler,J.; Corbane, C.; Schiavina, M.; Freire, S.; Sabo, F.; Politis, P.; Esch, T. & Pesaresi, M. (2019). The Generalised Settlement Area: mapping the Earth surface in the vicinity of built-up areas, International Journal of Digital Earth, DOI: 10.1080/17538947.2018.1550121.

Galabov, V. (2021). Demand for compute remains strong in 1Q21. Retrieved from https://omdia.tech.informa.com/blogs/2021/demand-for-compute-remains-strong-in-1q21 on 27th May 2021.

Garaway, I & Lewis, M & Bradley, P. & Radebaugh, R. (2011). Measured and Calculated Performance of a High Frequency, 4 K Stage, He-3 Regenerator. Cryocoolers. 16. Additionally, the picture is accessible through the following link https://www.researchgate.net/publication/265990902_Measured_and_Calculated_Performance_of_a_High_Frequency_4_K_Stage_He-3_Regenerator as of 14th June 2021.

Ge, X.; Tu, S.; Maro, G.; Wang, C.-X. and Han, T. (2016). 5G ultra-dense cellular networks. IEEE Wireless Communications, Vol. 23, 1, pages 72 – 79. 10.1109/MWC.2016.7422408.

Gerst, M.D., Graedel, T.E., (2008). In-use stocks of metals: status and implications. Environmental Science & Technology 42, 7038e7045.

Graedel, T. E., Barr, R., Chandler, C., Chase, T., Choi, J., Christoffersen, L., Friedlander, E., Henly, C., Jun, C., Nassar, N. T., Schechner, D., Warren, S., Yang, M., & Zhu, C. (2012). Methodology of Metal Criticality Determination. *Environmental Science & Technology*, *46*(2), 1063–1070. https://doi.org/10.1021/es203534z

Graedel, T. E., Harper, E. M., Nassar, N. T., Nuss, P., & Reck, B. K. (2015). Criticality of metals and metalloids. Proceedings of the National Academy of Sciences of the United States of America, 112(14). 4257 LP–4262 LP. Retrieved from http://www.pnas.org/content/112/14/4257.abstract

Graedel, T.E., and Nuss, P. (2014). Employing considerations of criticality in product design. JOM 66, 2360–2366.

Grandell, L., Lehtilä, A., Kivinen, M., Koljonen, T., Kihlman, S., Lauri, L.S., (2016). Role of critical metals in the future markets of clean energy technologies. Renew. Energy. https://doi.org/10.1016/j.renene.2016.03.102.

Griffin, G., Gaustad, G., & Badami, K. (2019). A framework for firm-level critical material supply management and mitigation. *Resources Policy*, *60*, 262 - 276. https://doi.org/10.1016/j.resourpol.2018.12.008.

GSMA (2020). The Mobile Economy 2020. Retrieved from https://data.gsmaintelligence.com/api-web/v2/research-file-download?id=51249388&file=2915-260220-Mobile-Economy.pdf on 20th May 2021.

Habib, K., Hamelin, L., & Wenzel, H. (2016). A dynamic perspective of the geopolitical supply risk of metals. Journal of Cleaner Production, 133, 850–858. Retrieved from http://www.sciencedirect.com/science/article/pii/S095965261630590X

Hagelueken, C. (2014). Recycling of (critical) metals. Crit. Met. Handb. 41–69.

Hedbrant, J., (2003). Structuring Empirical Knowledge on Environmental Issues. Urban Heavy Metal Metabolism. PhD thesis. Linköping Studies in Arts and Science2 83, Linköping, Sweden.

Hefferman, O. (2019), Deep-sea dilemma: Mining the ocean floor could solve mineral shortages – and lead to epic extinctions in some of the most remote ecosystems on Earth, Nature, 571, https://media.nature.com/original/magazine-assets/d41586-019-02242-y/d41586-019-02242-y.pdf

Helbig, C.; Wietschel, L.; Thorenz, A.; Tuma, A. (2016). How to evaluate raw material vulnerability – An overview. Resources Policy 48 (2016) 13 – 24. http://dx.doi.org/10.1015/j.resourpol.2016.02.003

Hofmann, M.; Hofmann, H.; Hagelueken, C.; Hool, A. (2018). Critical raw materials: A perspective from the materials science community. Sustainable Materials and Technologies 17 (2018) e00074. https://doi.org/10.1016/j.susmat.2018.e00074

Huawei (2020). Green 5G: Building a sustainable world. Retrieved from https://www-file.huawei.com/-/media/corp2020/pdf/public-policy/green_5g_building_a_sustainable_world_v1.pdf?la=en on 3rd May 2021.

International Energy Agency (2021) (IEA). The Role of Critical Minerals in Clean Energy Transition. World Energy Outlook Special Report.

Ioannidou, D.; Heeren N.; Sonnenmann, G.; Habert, G. (2019). The future in and of criticality assessments. Journal of Industrial Ecology. Vol. 23 (4), p.751 – 766. https://doi.org/10.1111/jiec.12834.

International Resource Panel (2011). Recycling Rates of Metals. A Status Report. ISBN: 978-92-807-3161-3. Retrieved from https://www.resourcepanel.org/reports/recycling-rates-metals on 18th June 2021.

International Resource Panel (2013). Metal Recycling: Opportunities, Limits, Infrastructure. United Nations Environment Programme, Nairobi.

Joshi, S. K., Aktas, D., Wengerowsky, S., Lončarić, M., Neumann, S. P., Liu, B., . . . Ursin, R. (2020). A trusted node–free eight-user metropolitan quantum communication network. Science Advances, 6(36), Eaba0959.

Juneja, S.; Pratap, R.; Sharma, R. (2021). Semiconductor technologies for 5G implementation at millimeter wave frequencies – Design challenges and current state of work. Engineering Science and Technology, an International Journal 24, 205 – 217. https://doi.org/10.1016/j.jestch.2020.06.012.

Kasulaitis, B., Babbitt, C.W., and Tyler, A.C. (2020). The role of consumer preferences in reducing material intensity of electronic products. J. Ind. Ecol., jiec.13052.

Kleinmagd, T. (2020). Material criticality for service providers: Assessment framework and outlook on mitigation strategies. A case study for a Dutch telecom provider. Master's Thesis for the study program of Industrial Ecology.

Kolotzek, C., Helbig, C., Thorenz, A., Reller, A., & Tuma, A. (2018). A company-oriented model for the assessment of raw material supply risks, environmental impact and social implications. *Journal of Cleaner Production*, *176*, 566–580. https://doi.org/10.1016/j.jclepro.2017.12.162.

KPN (2020). The Technology Book. The technology trends KPN has on its radar.

KPN (2020a). The Network of the Netherlands. Retrieved from https://www.overons.kpn/en/the-company/our-mission on 15th December 2020.

KPN (2020b). Dutch to the core. Retrieved from https://www.overons.kpn/en/kpn-in-the-netherlands/our-network/our-network-vision on 15th December 2020.

KPN (2020c). Network stability in 2017 – 2019. Retrieved from

https://www.overons.kpn/downloads/Network-availability.pdf on 15th December 2020.

KPN (2020d). KPN again one of the most sustainable telecom companies in the world (DJSI). Retrieved from https://www.overons.kpn/en/news/2020/kpn-again-one-of-the-most-sustainable-telecom-companies-in-the-world-djsi on 15th December 2020.

Krook, J.; Carlsson, A.; Eklund, M.; Fraendegard, P. and Svensson, N. (2011). Urban mining: hibernating copper stocks in local power grids. Journal for Cleaner Production, 19, 1052 – 1056. doi:10.1016/j.jclepro.2011.01.015.

Ku, A. (2018). Anticipating critical materials implications from the Internet of Things (IOT): Potential stress on future supply chains from emerging data storage technologies. Sustainable Materials and Technologies 15, 27 – 32. http://dx.doi.org/10.1016/j.susmat.2017.10.001.

Kuziak, R., Kawalla, R., and Waengler, S. (2008). Advanced high strength steels for automotive industry: a review. Arch. Civ. Mech. Eng. 8, 103–117.

Lacy, P.; Keeble, J.; McNamara, R.; Rutqvist, J.; Haglund, T.; Cui, M.; Cooper, A.; Pettersson, C.; Kevin, E.; Buddemeier, P.; et al. (2014). Circular Advantage: Innovative Business Models and Technologies to Create Value in a World without Limits to Growth; Accenture: Chicago, IL, USA, 2014.

Lenntech (2021a). Dysprosium – Dy. Chemical properties of dysprosium – Health effects of dysprosium – Environmental effects of dysprosium. Retrieved from https://www.lenntech.com/periodic/elements/dy.htm on 28th May 2021.

Lenntech (2021b). Erbium – Er. Chemical properties of erbium – Health effects of erbium – Environmental effects of erbium. Retrieved from https://www.lenntech.com/periodic/elements/er.htm on 1st June 2021.

Lenntech (2021c). Praseodymium – Pr. Chemical properties of praseodymium – Health effects of praseodymium – Environmental effects of praseodymium. Retrieved from https://www.lenntech.com/periodic/elements/pr.htm on 1st June 2021.

Lenntech (2021d). Ruthenium – Ru. Chemical properties of ruthenium – Health effects of ruthenium – Environmental effects of ruthenium. Retrieved from https://www.lenntech.com/periodic/elements/ru.htm on 1st June 2021.

Lenntech (2021e). Samarium – Sm. Chemical properties of samarium – Health effects of samarium – Environmental effects of samarium. Retrieved from https://www.lenntech.com/periodic/elements/sm.htm on 1st June 2021.

Lenntech (2021f). Terbium – Tb. Chemical properties of terbium – Health effects of terbium – Environmental effects of terbium. Retrieved from https://www.lenntech.com/periodic/elements/tb.htm on 1st June 2021.

Leopold, G. (2020). Latency Needs Driving an Edge Server Boom. Retrieved from https://www.enterpriseai.news/2020/07/28/latency-needs-driving-an-edge-server-boom/ on 27th May 2021.

Lewandowski, M. (2015). Designing the Business Models for Circular Economy – Towards the Conceptual Framework. Sustainability, 2016, 8, 43, doi:10.3390/su8010043.

Lloyd, S., Lee, J., Clifton, A., Elghali, L., and France, C. (2012). Ecodesign through environmental risk management: a focus on critical materials. In Design for Innovative Value towards a Sustainable Society (Springer Netherlands), pp. 374–379.

Lobos, A., and Babbitt, C. (2013). Integrating emotional attachment and sustainability in electronic product design. Challenges 4, 19–33, https://doi.org/10.1111/jiec.13052.

Madsen, H.; Burtschy, B.; Albeanu, G.; Popentiu-Vladicescu, F. (2013). Reliability in the utility computing era: towards reliable fog computing. Paper presented at the 20th international conference on systems, signals and image processing (IWSSIP), Bucharest, 7–9 July 2013.

Månberger, A., Stenqvist, B., 2018. Global metal flows in the renewable energy transition: exploring the effects of substitutes, technological mix and development. Energy Policy 119, 226‑241. https://doi.org/10.1016/j.enpol.2018.04.056.

Manners, D. (2017). Semi units to hit a trillion next year. Retrieved from https://www.electronicsweekly.com/news/business/semi-units-hit-trillion-next-year-2017-03/ on 10th May 2021.

Matos C.T, Ciacci, L; Godoy León, M.F.; Lundhaug, M.; Dewulf, J.; Müller, D.B.; Georgitzikis, K.; Wittmer, D.; Mathieux, F. (2020). Material System Analysis of five battery-related raw materials: Cobalt, Lithium, Manganese, Natural Graphite, Nickel, EUR 30103 EN, Publication Office of the European Union, Luxembourg, ISBN 978-92-76-16411-1, doi:10.2760/519827, JRC119950.

Mccarthy, A., Dellink, R., and Bibas, R. (2018). The Macroeconomics of the Circular Economy Transition: A Critical Review of Modelling Approaches (OECD Publishing).

Mmta (2016a). Ho – Holmium. Retrieved from https://mmta.co.uk/metals/ho/#:~:text=Reserves%20of%20holmium%20are%20estimated,about%2010%20tonnes%20per%20year on 28th May 2021.

Mmta (2016b). Tm – Thulium. Retrieved from https://mmta.co.uk/metals/tm/ on 1st June 2021.

Monnet, A.; Ait Abderrahim, A. (2018). Report on Major Trends Affecting Future Demand for Critical Raw Materials. SCREEN Project D.2.2., 2018.

Moore, N. (2018). How to do research. The practical guide to designing and managing research projects. https://doi.org/10.29085/9781856049825.

Moss, R., Tzimas, E., Kara, H., Willis, P., & Kooroshy, J. (2011). Critical metals in strategic energy technologies: Assessing rare metals as supply-chain bottlenecks in low-carbon energy technologies. Luxembourg: JRC Publications.

National Agenda Photonics (2018). National Agenda Photonics 2018. Retrieved from https://nationaleagendafotonica.nl/wp-content/uploads/2018/12/National_Agenda_Photonics_spreads_EN.pdf on 4th May 2021.

Nigam, H.; Mathur, M.; Arora, M.; Singh, R. (2020). Enhancing gain with multiple beams for four element phased array microstrip antenna using Rogers substrate material for 5G application. Materials Today: Proceedings 30, 203 – 209. https://doi.org/10.1016/j.matpr.2020.06.103.

Norman, D. (1998). The Design of Everyday Things (Basic Books, Inc.). ISBN 978-0-465-05065-9.

OECD (2020a). OECD broadband statistics update. Retrieved from https://www.oecd.org/sti/broadband/broadband-statistics-update.htm on 7th June 2021.

OECD (2020b). OECD share in world GDP stable at around 50% in PPP terms in 2017. Retrieved from https://www.oecd.org/sdd/prices-ppp/oecd-share-in-world-gdp-stable-at-around-50-per-cent-in-ppp-terms-in-2017.htm on 7th June 2021.

Palizban, N.; Szyszkowicz, S. and Yanikomeroglu, H. (2017). Automation of millimeter wave network planning for outdoor coverage in dense urban areas using wall-mounted base stations. IEEE Wireless Communications Letters, Vol. 6, Issue 2, pages 206 – 209. 10.1109/LWC.2017.2659732.

Patrahau, I.; Singhvi, A.; Rademaker, M.; van Manen, H.; Kleijn, R,; van Geuns, J. (2020). Securing Critical Materials for Critical Sectors. Policy options for the Netherlands and the European Union. The Hague Center for Strategic Studies. ISBN/EAN: 9789492102805.

Peck, D.; Huisman, J.; Leovik, A.; Ljunggren, M.; Chancerel, P.; Habib, H.; Wagner, M.; Sinha-Khetriwal, D. (2020). CRM trends and scenarios Deliverable 2.4..

Peck, D., Kandachar, P.; Tempelman, E. (2015). Critical materials from a product design perspective. Mater. Des. 65, 147–159.

Photonics21 – European Technology Platform (2017). Market Research Study Photonics 2017. Photonic Public Private Partnership.

Polverini, D.; Ardente, F.; Sanchez, I.; Mathieux, F.; Tecchio, P.; Beslay L. (2018). Resource Efficiency, Privacy and Security by Design: A First Experience on Enterprise Servers and Data Storage Products Triggered by a Policy Process. Computers and Security, Vol. 76, 2018, pp.295-310.

Precious Metals Commodity Management (2020). Market Trend Report. Silver's role in a future 5G connected world. The Silver Institute.

Raw Materials Information System (RMIS) (2019). Artisanal and Small Scale-Mining. Retrieved from https://rmis.jrc.ec.europa.eu/?page=artisanal-and-small-scale-mining-a6f8a3 on 24th June 2021.

Razavi, M. (2018). An Introduction to Quantum Communication Networks. Or, how shall we communicate in the quantum era? Morgan & Claypool Publishers, United Kingdom, DOI 10.1088/978-1-6817-4653-1.

Richdale, K. (2017). Why Quantum Technologies matter in Critical Infrastructure and IOT. Defense Future Technologies. What we see on the horizon. Armasuisse Science and Technology. ISBN: 978-3-9524890-0-0.

Riddle, M., Macal, C. M., Conzelmann, G., Combs, T. E., Bauer, D., & Fields, F. (2015). Global critical materials markets: An agent-based modeling approach. Resources Policy, 45, 307–321.

Schrijvers, D.; Hool, A.; Blengini, G.A.; Chen, W.; Dewulf, J.; Eggert, R.; van Ellen, L.; Gauss, R.; Goddin, J.; Habib, K.; Hagelüken, C.; Hirohata, A.; Hofmann-Amtenbrink, M.; Kosmol, J.; Le Gleuher, M.; Grohol, M.; Ku, A.; Lee, M.; Liu, G.; Nansai, K.; Nuss, P.; Peck, D.; Reller, A.; Sonnemann, G.; Tercero, L.; Thorenz, A.; Wäger, P. A. A review of methods and data to determine raw material criticality, Resources, Conservation and Recycling, Volume 155, 2020, 104617, ISSN 0921-3449, https://doi.org/10.1016/j.resconrec.2019.104617.

Section (2020). 7 Predictions in Edge Computing for 2021. Retrieved from https://www.section.io/blog/7-edge-computing-predictions-2021/ on 14th April 2021.

Statista (2021). Natural rubber production worldwide from 2000 to 2020. Retrieved from https://www.statista.com/statistics/275387/global-natural-rubber-production/#:~:text=Natural%20rubber%20production%20worldwide%20in,natural%20rubber%20was%20produced%20globally on 28th May 2021.

Sprecher, B.; Daigo, I.; Murakami, S.; Kleijn, R.; Vos, M.; Kramer, G. J. (2015). Framework for Resilience in Material Supply Chains, With a Case Study from the 2010 Rare Earth Crisis. Environ. Sci., 49, 6740 – 6750. DOI: 10.1021/acs.est.5b00206.

Sunyaev, A. (2020). Internet Computing. Principles of Distributed Systems and Emerging Internet-Based Technologies. Springer Nature Switzerland AG. https://doi.org/10.1007/978-3-030-34957-8.

Sweeney, S. J.; Mukherjee, J. (2017): Optoelectronic Devices and Materials. – In: S. Kasap, P. C. (Hrsg.): Springer Handbook of Electronic and Photonic Materials. Perspectives on electronic and photonic materials. Cham.

Telia Company & Accenture (2021). The Shift. The role of telcos in the circular economy. A report by Telia Company and Accenture. Retrieved from https://www.teliacompany.com/globalassets/telia-company/documents/sustainability/the-shift--the-role-of-telcos-in-the-circular-economy.pdf on the 24th June 2021.

Tercero Espinoza, L. (2019). Report on the Future Use of Critical Raw Materials. SCREEN Project D.2.3., 2019.

Tercero Espinoza, L., Schrijvers, D., Chen, W. Q., Dewulf, J., Eggert, R., Goddin, J., Habib, K., Hagelüken, C., Hurd, A. J., Kleijn, R., Ku, A. Y., Lee, M. H., Nansai, K., Nuss, P., Peck, D., Petavratzi, E., Sonnemann, G., van der Voet, E., Wäger, P. A., ... Hool, A. (2020). Greater circularity leads to lower criticality, and other links between criticality and the circular economy. *Resources, Conservation and Recycling*, *159*, [104718]. https://doi.org/10.1016/j.resconrec.2020.104718.

Tukker, A. (2004). Eight Types of Product Service Systems: Eight Ways To Sustainability? Bus. Strateg. Environ., 13, 246–260.

UNEP (2010). Metal Stocks in Society. Scientific Synthesis. Retrieved from https://wedocs.unep.org/bitstream/handle/20.500.11822/8438/Metal_Stocks_EN.pdf?sequence=1&isAllowed=y on 24th June 2021. ISBN: 978-92-807-3082-1.

United Nations General Assembly (2016). Resolution adopted by the Human Rights Council on 1st July 2016. 32/13 The promotion, projection and enjoyment of human rights on the Internet.

USGS (2021). Mineral Commodities Summaries 2021: U.S. Geological Survey, 200 p. https://doi.org/10.3133/mcs2021. ISBN 978-1-4113-4398-6.

Wang, Q.; Zhao, X.; Lv, Z.; Ma, X.; Zhang, R. and Lin, Y (2020). Optimizing the ultra-dense 5G base stations in urban outdoor areas: Coupling GIS and heuristic optimization. Sustainable Cities and Societies, Vol. 63, 102445. https://doi.org/10.1016/j.scs.2020.102445.

Wang, X., Gaustad, G., Babbitt, C.W., Bailey, C., Ganter, M.J., and Landi, B.J. (2014). Economic and environmental characterization of an evolving Li-ion battery waste stream. J. Environ. Manage. 135, 126–134.

Wani, Z.; Abegaonkar, M. P. and Koul, S.K. (2018). A 28-GHz Antenna for 5G MIMO Applications, Progress In Electromagnetics. Research Letters 78, 73–79.

Watari, T.; McLellan, B. C.; Giurco, D.; Dominish, E.; Yamasue, E.; Nansai, K. (2019). Total material requirement for the global energy transition to 2050: A focus on transport and electricity. Resources, Conservation & Recyling, 148 (2019), 91 – 103. https://doi.org/10.1016/j.resconrec.2019.05.015.

WBOC (2021). Edge Server Market Share, Growth Statistics 2021 - Regional Production Volume with Significant CAGR of 8.13%, Business Development Analysis, Consumption, Revenue, Sales, Competitive Environment and Forecast till 2027. Retrieved from https://www.wboc.com/story/43873508/edge-server-market-share-growth-statistics-2021-regional-production-volume-with-significant-cagr-of-813-business-development-analysis-consumption on the 31st May 2021.

Widmer, R.; Wäger, R. (2013). ICT Hardware – Materials: Scarce Metals as Raw Materials for ICTs: Do we care enough?

Wiseley, D.; Wang, N. and Tafazolli, R. (2018). Capacity and cost for 5G networks in dense urban areas. IET Communication, Vol. 12, Issue 19, pages 2502 – 2520. https://doi.org/10.1049/iet-com.2018.5505.

Yole Développement (2020). Optical Transceivers for Datacom & Telecom. Market and Technology Report. From Technologies to Markets. Retrieved from https://s3.i-micronews.com/uploads/2020/06/YDR20120-Optical-Transceivers-for-Datacom-Telecom-2020-Sample.pdf on 14th April 2021.

Young, S. B. (2018). Responsible sourcing of metals: certification approaches for conflict minerals and conflict-free metals. Int J Life Cycle Assessment, 23, 1429 – 1447. DOI 10.1007/s11367-015-0932-5.

Zhao, H.; Pinna, S.; Sang, F.; Song, B.; Brunelli, S. T. S.; Coldren, L. A. and Klamkin, J. (2019). High-Power Indium Phosphide Photonic Integrated Circuits. IEEE Journal of Selected Topics in Quantum Electronics, Vol. 25, No. 6, DOI 10.1109/JSTQE.2019.2908788.

Appendix Chapter 4 – Critical Raw Materials in Future Technologies

The following subchapters represent the appendices for the first phase of the research: Identification of CRMs contained in future telecommunication technologies.

Appendix A1: 5G Technology – Critical Raw Materials in Equipment

The following Tables A1.1 – A1.2 represent the raw data retrieved from experts about CRMs contained in 5G Technologies.

Table A1.1: CRM contents of different equipment of the Radio Access Network.

Equipment of RAN	Critical Raw Materials
Equipment A	Be, Bi, B, Co, Ga, Ge, Mg, P, Si
Equipment B	Be, Bi, B, Co, Ga, Mg, P, Si, PGM
Equipment C	Be, Bi, B, Co, Ga, Ge, Mg, Nb, P, Si, V, PGM
Equipment D	Be, Cr, Co, Ga, Ge, In, Mg, Sb, Si, Ta, PGM, REE
Equipment E	Be, Cr, Co, Ga, Ge, Mg, Si, PGM, REE

Table A1.2: CRM contents of different equipment of the Mobile Network, Remote Ratio Unit and Antenna.

Equipment of 5G	Critical Raw Materials
Mobile Equipment	Ba, Bi, Ce, Co, Dy, Gd, Ga, Ge, Hf, In, La, Mg, Nd, Nb, P, Pd, Pr, Pt, Rh, Ru, Sb, Sm, Si, Ta, W, V, Y
Remote Radio Unit	B, Ba, Be, Bi, Co, Ga, Graphite, In, Mg, Natural Rubber, Nb, Nd, P, Pd, Pt, Ru, Sb, Si, Sm, Sr, Ta, Tb, Ti, V, W, Y
Antenna	Graphite, Mg, Si

Appendix A2: 5G Technology – Supply Risk & Occurrence Assessment

The below Table A2.1 represents the occurrence analysis of the 5G Technology equipment.

Table A2.1: Occurrence of CRMs across different 5G equipment.

	RAN	Mobile	Remote Radio Unit	Antenna	Highest frequently occurring CRMs
Antimony Sb	X	X	X		3
Baryte Ba		X	X		3
Beryllium Be	X		X		2
Bismuth Bi	X	X	X		3
Borates B	X		X		2
Natural Graphite C			X	X	2
Cerium Ce	X	X			2
Cobalt Co	X	X	X		3
Dysprosium Dy	X	X			2
Erbium Er	X				1
Europium Eu	X				1
Gadolinium Gd	X	X			2
Gallium Ga	X	X	X		3
Germanium Ge	X	X			2
Hafnium Hf		X			1
Holmium Ho	X				1
Indium In	X	X	X		3
Iridium Ir	X				1
Lanthanum La	X	X			2
Lithium Li					0
Lutetium Lu	X				1
Magnesium Mg	X	X	X	X	4
Neodymium Nd	X	X	X		3
Niobium Nb	X	X	X		3
Palladium Pd	X	X	X		3
Phosphorous P	X	X	X		3
Platinum Pt	X	X	X		3
Praseodymium Pr	X	X			2
Rhodium Rh	X	X			2
Ruthenium Ru	X	X	X		3
Samarium Sa	X	X	X		3
Scandium Sc	X				1
Silicon Si	X	X	X	X	4
Strontium Sr			X		1
Tantalum Ta	X	X	X		3

Terbium Tb	X		X		2
Thulium Tm	X				1
Titanium Ti			X		1
Tungsten W		X	X		2
Vanadium V	X	X	X		3
Yttrium Y	X	X	X		3
Ytterbium Yb	X				1
Bauxite					0
Coking Coal					0
Fluorspar					0
Natural Rubber			X		1
Phosphate Rock					0
Total per Technology	35	27	26	3	

Furthermore, the below Table A2.2. represents the raw data used for the Criticality Matrix.

Table A2.2.: 5G Equipment Criticality Matrix: Occurrence x Supply Risks.

	SR	Occ.		SR	Occ.		SR	Occ.		SR	Occ.
Antimony Sb	2.0	3	Gallium Ga	1.3	3	Palladium Pd	1.3	3	Thulium Tm	6.1	1
Baryte Ba	1.3	3	Germanium Ge	3.9	2	Phosphorous P	3.5	3	Titanium Ti	1.3	1
Beryllium Be	2.3	2	Hafnium Hf	1.1	1	Platinum Pt	1.8	3	Tungsten W	1.6	2
Bismuth Bi	2.2	3	Holmium Ho	6.1	1	Praseodymium Pr	5.5	2	Vanadium V	1.7	3
Borates B	3.2	2	Indium In	1.8	3	Rhodium Rh	2.1	2	Yttrium Y	4.2	3
Natural Graphite C	2.3	2	Iridium Ir	3.2	1	Ruthenium Ru	3.4	3	Ytterbium Yb	6.1	1
Cerium Ce	6.2	2	Lanthanum La	6.0	2	Samarium Sa	6.1	3	Bauxite	2.1	0
Cobalt Co	2.5	3	Lithium Li	1.6	0	Scandium Sc	3.1	1	Coking Coal	1.2	0
Dysprosium Dy	6.2	2	Lutetium Lu	6.1	1	Silicon Si	1.2	4	Fluorspar	1.2	0
Erbium Er	6.1	1	Magnesium Mg	3.9	4	Strontium Sr	2.6	1	Natural Rubber	1.0	1
Europium Eu	3.7	1	Neodymium Nd	6.1	3	Tantalum Ta	1.4	3	Phosphate Rock		0

The below Figure A2.1 – A2.4 represent the results of the Occurrence x Supply Risk assessment per device.

5G Radio Access Network

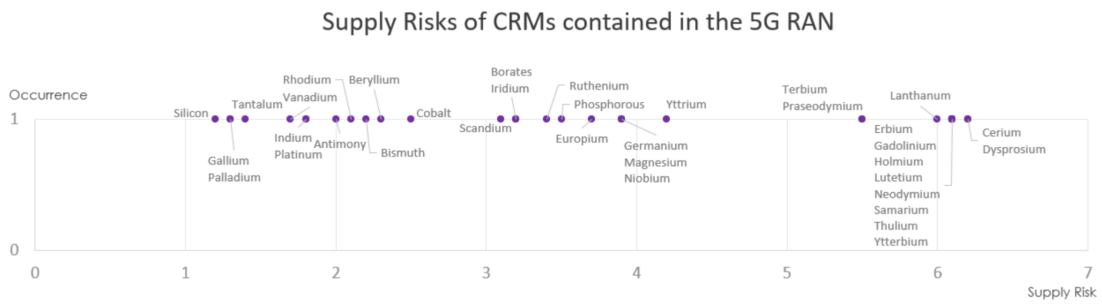


Figure A2.1.: Supply Risks of CRMs contained in the 5G RAN.

For the 5G RAN, CRMs across all different supply risks can be identified. The contained CRMs that are associated with the highest supply risks include Ce, Dy, Er, Gd, Ho, Lu, Nd, Sm, Tm, Yb and La. Also Tb and Pr are associated with relative high supply risks. The remaining contained CRMs are rather associated with low or medium high supply risks.

5G Mobile Network

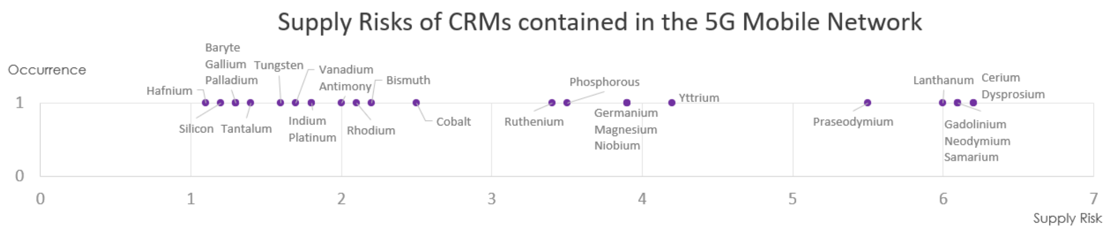


Figure A2.2: Supply Risks of CRMs contained in the 5G Mobile Network.

When looking at the 5G Mobile Network, the CRMs contained and associated with the highest supply risks include Ce, Dy, Gd, Nd, Sm and La. Also Pr is associated with relatively high supply risks. The remaining CRMs do rather have low or medium high supply risks.

5G Remote Radio Unit

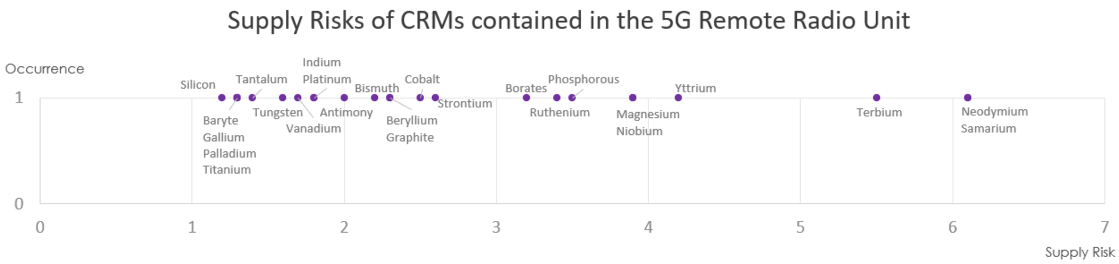


Figure A2.3.: Supply Risks of CRMs contained in the 5G RRU.

For the 5G RRU, solely three CRMs could be identified that are associated with high supply risks. These include Nd, Sm and Tb. Thus, they might cause a threat on the manufacturing of the RRU. The remaining CRMs are rather associated with low or medium supply risks.

5G Antenna

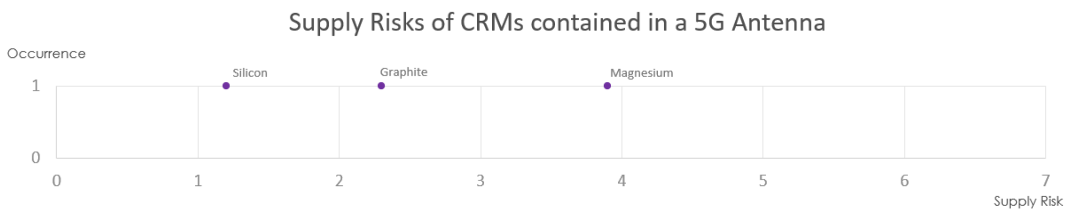


Figure A2.4.: Supply Risks of CRMs contained in the 5G Antenna.

Finally, there are no CRMs with high supply risks contained in an antenna. The CRM Si has quite low supply risks. Natural Graphite also has rather low supply risks. Mg is associated with medium high supply risks.

Appendix B1: Photonics – Interview and E-mail Communication summaries

Interview with Professor A for Photonics Integration on 12th December 2020

According to Professor A, Photonics as a technology includes a Photonic Integrated Circuit (PIC) and outside of the PIC packaging. Until now the main focus lays on PICs for the telecom sector, however they are working on making these also available for other sectors, such as the healthcare or automotive sector. However, in the best case photonics are capable of replacing all electronics in the future.

A PIC consists of a lot of elements from the periodic table. Firstly they consist of InP, but there are also Si PICs. Those silicon can be more found in data centers, however they are not entirely feasible. Furthermore, also a mix of InP and Si is possible. Additional metals that can be found include Ga, As, Pt and REEs.

Outside of a PIC, there is the so-called packaging. This includes exemplarily the growing of silicon and indium phosphide crystals, epitaxy, which includes the growing of nano-scale layers and wavers, which are a big problem for recycling. Furthermore, there are isolators, which are currently tried to replace them, however they are widely used and include magnetic optical devices and rare earth elements. Moreover, there are optical and electrical connections. Water and oxygen degrades the chips, thus a vacuum and nitrogen scaling is also of importance. Looking at the thermal expansion, aluminum, nitrate and special metals are of importance.

According to Professor A it is wise to check RoHS and Reach Compliance in order to gather more information about the raw material contents of Photonics, but also on environmental implications.

Packaging outside of the PIC:

- *Epitaxy (nano-scale layers)* – this is wafer growth and presumably this includes ingot growth as well? The substrates are 99% of the materials used.
- *Wafer-scale processing* – including lithography, etch, deposition, singulation, thinning etc. Basically the clean room processing
- *Isolators (Magnetic Optical Devices) – the package including resonators, reflectors, solders, thermo-electric devices, ceramics, etc*
- *Optical Equipment – switches, multiplexers, interleavers, patch-panels, fiber amplifiers. These can involve PICs (above two items)*
- *Electrical Equipment – heat removal technologies for example; Signals flip back and forth between media (optical fiber, air, electrical traces, electrical cables, twisted pair) depending on where they are in the network.*
- *Connection between both equipment*

Interview with Professor B for High Capacity Optical Transmission on 19th March 2021

In the beginning of the interview, Professor B explained that his research focuses on high capacity transmission systems, for which Photonics is an essential part. Furthermore, another part of his research concerns securing that networks cannot be exposed to cyber criminality for which Quantum Technologies play a role. Since materials play a crucial role in the development of those two technologies, there is a strong awareness about Critical Raw Materials.

When looking into the future of devices, the trends goes towards more and more integrating lower level components, improving material consumption and making products more dense by minimizing single components. This also has the effect that supply chains are going to be more integrated. This was different 10 years ago.

The next step was to discuss about specifically the Photonic amplifier device. Basically, for the manufacturing of a Photonic amplifier, there are mainly 3 -5 materials of importance:

- In
- P
- Si
- Ge
- SiGe
- Ag

In addition to that there need to be amplifying material, which is doped with the above depending on the preferred amount of interaction between the Photons. Those materials include:

- Erbium: Extremely critical element for transmitting light, can double the amount of photons (multiplier effect), can also multiply the noise
- Bismuth: Lower frequencies need Bismuth for transmitting, thus allows shorter wavelengths for lasers and the material is also important for expanding the capacity of Photonic devices
- Thulium: working on 2micro meter area with 15x15mm

Lastly, Professor B for High Capacity Optical Transmission explained the amount of optical devices that are going to be needed in the network and how they are related to one another. In general, there are 80 different wavelengths. For each of the 80 wavelengths, one specific transmitter and one specific receiver is needed. Those need to be connected in both ways. Furthermore, in case there is a second receiver that should also receive the signal of the transmitter, an optical switch is required in the middle to redirect the signal to the second receiver:

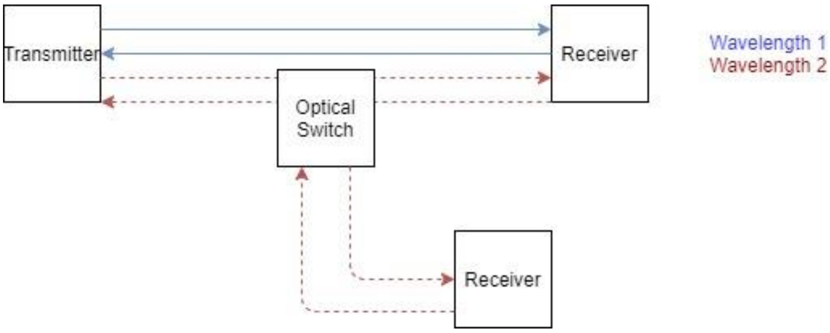


Figure B1.1: Simplified version of Photonics devices in the network.

Expressing this in amounts of devices needed, 1 per direction per wavelength is needed. And the same for sending the signal back. Thus, it is necessary to know how many links are there in the network.

As a last point, quickly MEMS switches as part of Quantum Routers were discussed. MEMS Switches are mechanically moving switches that are able to reflect incoming light. This can be done on either the micro level or the nano level. What happens is that the incoming light is manipulated and processed. Furthermore, it can also be used for controlling the beam.

Interview with Professor C for Electro-Optical Communication Systems on 24th March 2021

During the interview, the most important CRMs were mentioned and short explanatory notes were given. They can be read below.

- Bi: Mostly for fibers
- In: Very important
- Ga: In the Photonics Detector
- Ge
- Nb: Not very often used
- Li: Very important for Photonics Amplifiers due to the LiNb-Elements
- P: Used
- Graphite: Not yet used
- HREE: Especially Erbium highly used for Photonic Amplifiers

Furthermore, it was mentioned that within a transceiver, the receiver part consists of GaAs and the transmitting part of InP.

Interview and E-mail Communication with Supplier A for Photonic Devices on 12th January 2021, 26th February 2021 and 9th March 2021

According to Supplier A, a PIC consists of 99% InP, which has an atomic composition of 1:1 (In : P). Further elements and materials contained in a PIC are small amount of Ag, Ga, As, Ti and Pt. Besides that they also include gases, such as chlorine for edging the semiconductors.

Furthermore, there are different parts of the PIC, which are 'build' by different technologies. One includes epitaxy, which is needed for growing layers of InP material with certain compositions. Epitaxy is called a 'reactor' that converts gas sources into the layers which are then contained in the PIC. Additionally, another technology is waver-processing. In order to grow those wavers, InP is required, as well as gold. In general, for all those technologies the same materials are approximately used and can be estimated the same.

The next content of the interview included the build-up of a typical telecom device. Such a typical device is a transceiver within a server, which is used in data centers. It is build up in a way that the PIC represents somehow the brain of a 'USB-Stick'-like device, additional to optical components, electronic components and a temperature control.

Supplier A further explained that optical signals are going into data centers through glass fiber cables. Within the data centers they are firstly transferred into electronic signals but then transferred again to optical signals through lasers. All of these processes are associated with losses. It is clear as of today, that optical signals require less energy, thus this requires optical computing power.

Interview and E-mail Communication with Supplier B for Photonic Devices on 5th February 2021

The following gives an overview on the mentioned components and materials

- The housing (Outside)
    - Biggest part of the silver-colored frame
        - Alloy of Mg, Zn, Al and Cu
    - Ladch (Right silver part, next to the black thing on the left, but left of the screw)
        - Al
    - Silver part with the three horizontal lines on the left
        - Al
- The inside
    - Fiber (cm small)
        - Si
    - PCBA assembly
        - Connector lanes
            - Cu
        - Wires
            - Pure Au to bond the electrical parts (high impact on the performance)
    - Ceramics
        - AlN
    - Epoxys (Fluid parts)
        - Oil related products

        - Silver (very small part)
- Readily available materials
    - Regular glass

PCB

Furthermore, we discussed about PCBs. PCBs are always the same. It can be called the nervous system of the whole product. It makes sure that the different components can talk to each other.

How many of the devices do we need?

In order to incorporate it into the network, we need to place one at the antenna (transmitter) and one at the edge of the network as a receiver. One connection works with 10Gbit/s. Those two are then connected by wire. One connection works at 40km of length. For more information, check the product description file on the homepage.

Interview and E-mail Communication with Supplier C for Photonic Devices on 2nd April 2021

As part of the contact with Supplier C, mainly calculations on amounts of CRMs were conducted based on the before shared information from Supplier A and B. Additionally, CRMs were added, where additional information could be given.

Generally, a PIC is of the size 6-8mm^2 or 20-30mm^2. Furthermore, there are around 200 chips on one waver.

Appendix B2: Photonics - Raw Materials in Equipment

The following Table X gives an overview on the raw materials that were identified as part of the expert interviews. Information gathered from the interviews were aggregated and summarized in Table B2.1.

Table B2.1: Raw material content data of Photonic devices.

Photonic Device	Lower Level Component	Raw Material Contents
Photonic Transceiver	Photonic Integrated Circuits (PIC)	Ga, GaAs, Ge, InP, Pd, Pt, Ti
	Housing	Al, Cd, Cu, Mg, Pb, Zn
	Fiber	SiO2
	Ferrule	ZrO2
	Connector Lanes	Au, Cu, Polyimide
	Wires	Au
	Ceramics	AlN, AlO
	Epoxy	Au
	Heat sinks	CVD diamond, Mo
	Thermal Stabilization	Bi2Te3, PbTe, SiGe
	Solders	AuSn, Bi, In
	Electronics	Si
	Additional parts	Glass
Photonic Amplifier	General components	Bi, Er, Tl, Th, Yb
	Additional components	Al, Au, Ge, Si, Pr
	Electronics	Co, Si
Photonic Optical Switch	General components	Al, AlN, Ga, GaAs, Ge, InP, liquid crystal, Pt, Si, Si3N4
	Modulator	LiNbO3
	Lenses	Si
	Optical Fiber	Si
	Research components	Ba, phase change materials, Polymers, Ti, Ta

Appendix B3: Photonics – Supply Risk & Occurrence Assessment

Below Table B3.1 shows the occurrence of a CRMs contained in selected Photonics devices.

Table B3.1: Occurrence of CRMs in Photonics Equipment.

	Photonics Transceiver	Photonics Amplifier	Photonics Optical Switch	Highest frequently occurring CRMs
Antimony Sb				0
Baryte Ba			X	1
Beryllium Be				0
Bismuth Bi	X	X		2
Borates B				0
Natural Graphite C				0
Cerium Ce				0
Cobalt Co		X		1
Dysprosium Dy				0
Erbium Er		X		1
Europium Eu				0
Gadolinium Gd				0
Gallium Ga	X		X	2
Germanium Ge	X	X	X	3
Hafnium Hf				0
Holmium Ho				0
Indium In	X	X	X	3
Iridium Ir				0
Lanthanum La				0
Lithium Li			X	1
Lutetium Lu				0
Magnesium Mg	X			1
Neodymium Nd				0
Niobium Nb			X	1
Palladium Pd	X	X		2
Phosphorous P	X		X	2
Platinum Pt	X		X	2
Praseodymium Pr		X		1
Rhodium Rh				0
Ruthenium Ru				0
Samarium Sa				0
Scandium Sc				0
Silicon Si	X	X	X	3
Strontium Sr				0
Tantalum Ta			X	1
Terbium Tb				0
Thulium Tm				0
Titanium Ti	X		X	2
Tungsten W				0
Vanadium V				0
Yttrium Y				0
Ytterbium Yb		X		1
Bauxite				0
Coking Coal				0
Fluorspar				0
Natural Rubber				0
Phosphate Rock				0
Total per Technology				

As the second step the supply risks associated with the occurrence of CRMs in Photonic Devices is pictured within a Criticality Matrix. The raw data can be found in Table B3.2.

Table B3.2: Photonics Equipment Criticality Matrix: Occurrence x Supply Risks.

	SR	Occ.		SR	Occ.		SR	Occ.		SR	Occ.
Antimony Sb	2.0	0	Gallium Ga	1.3	2	Palladium Pd	1.3	2	Thulium Tm	6.1	0
Baryte Ba	1.3	1	Germanium Ge	3.9	3	Phosphorous P	3.5	2	Titanium Ti	1.3	2
Beryllium Be	2.3	0	Hafnium Hf	1.1	0	Platinum Pt	1.8	2	Tungsten W	1.6	0
Bismuth Bi	2.2	2	Holmium Ho	6.1	0	Praseodymium Pr	5.5	1	Vanadium V	1.7	0
Borates B	3.2	0	Indium In	1.8	3	Rhodium Rh	2.1	0	Yttrium Y	4.2	0
Natural Graphite C	2.3	0	Iridium Ir	3.2	0	Ruthenium Ru	3.4	0	Ytterbium Yb	6.1	1
Cerium Ce	6.2	0	Lanthanum La	6.0	0	Samarium Sa	6.1	0	Bauxite	2.1	0
Cobalt Co	2.5	1	Lithium Li	1.6	1	Scandium Sc	3.1	0	Coking Coal	1.2	0
Dysprosium Dy	6.2	0	Lutetium Lu	6.1	0	Silicon Si	1.2	3	Fluorspar	1.2	0
Erbium Er	6.1	1	Magnesium Mg	3.9	1	Strontium Sr	2.6	0	Natural Rubber	1.0	0
Europium Eu	3.7	0	Neodymium Nd	6.1	0	Tantalum Ta	1.4	1	Phosphate Rock		0
Gadolinium Gd	6.1	0	Niobium Nb	3.9	1	Terbium Tb	5.5	0			

The below Figure B3.1 – B3.3 show the results of the supply risk assessment per Photonics device.

Photonic Transceiver

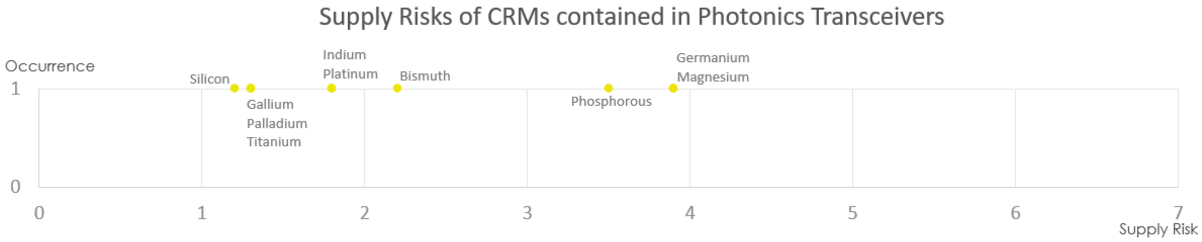


Figure B3.1: Supply risks of CRMs contained in a Photonics Transceiver

When looking at the CRMs contained in a Photonics Transceiver, it becomes clear that most of the CRMs are only associated with moderately high supply risks. The CRMs Ge, Mg and P are associated with the relatively highest supply risks, making them of central importance for the transceiver. The lowest supply risks are associated with the CRMs Si. Those relatively high supply risky CRMs can mainly be found in the lower level components PIC and Housing of the Photonics Transceiver.

Photonic Amplifier

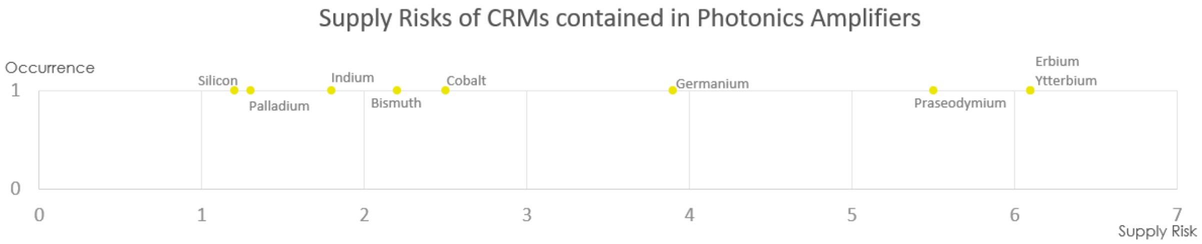


Figure B3.2: Supply Risks of CRMs contained in Photonics Amplifiers.

There are three CRMs contained in Photonic Amplifiers that are associated with very high supply risks. Those include Er, Pr and Yb. Not being able to supply these can cause a serious threat on the development of the technology. Furthermore, Ge is associated with moderately high risks. The CRMs Si, Pd or In do rather have lower supply risks and do thus not potentially harm.

Photonics Optical Switch

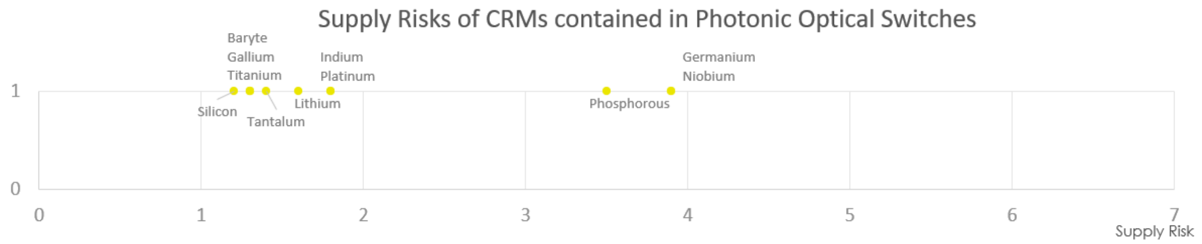


Figure B3.3: Supply Risks of CRMs contained in Photonic Optical Switches.

No high supply risks for CRMs contained in Photonic Optical Switches could be identified. However, the CRMs Ge, Nb and P are associated with moderately high supply risks. The remaining CRMs contained do not cause serious supply risks to the development of the technology.

Appendix C1: Edge Computing – Critical Raw Materials in Servers

The following Table C1.1 gives an overview on the raw materials contained in Edge Computing Servers.

Table C1.1: Overview on information retrieved from the excel file on Edge Computing Server as part of this study.

Edge Computing Device	Lower Lovel Components	Raw Material Contents
Edge Computing Server	Motherboard	B, B_2O_3, $BaTiO_3$, CuPZn, FeNiCo, GaAs, Ge, MgO, $Mg_3Si_4O_{10}(OH)_2$, Pd, RuO_2, Sb_2O_3, Si, Si_2O_3, Ta_2O_5, W
	Smart Storage Battery	$LiCoO_2$
	Fiber Optical Cable	Er
	Small Form Factor Hard Drive	Co, Dy, Nd
	Large Form Factor Hard Drive	Co, Dy, Nd
	High Speed Hard Drive	He
	Memory	Ce

Appendix C2: Edge Computing – Supply Risk & Occurrence Assessment

The below Table C2.1 represents the raw data of the assessment.

Table C2.1: Edge Computing Criticality Matrix: Occurrence x Supply Risks.

	SR	Occ.		SR	Occ.		SR	Occ.		SR	Occ.
Antimony Sb	2.0	1	Gallium Ga	1.3	1	Palladium Pd	1.3	1	Thulium Tm	6.1	0
Baryte Ba	1.3	0	Germanium Ge	3.9	1	Phosphorous P	3.5	1	Titanium Ti	1.3	1
Beryllium Be	2.3	0	Hafnium Hf	1.1	0	Platinum Pt	1.8	0	Tungsten W	1.6	1
Bismuth Bi	2.2	0	Holmium Ho	6.1	0	Praseodymium Pr	5.5	0	Vanadium V	1.7	0
Borates B	3.2	1	Indium In	1.8	0	Rhodium Rh	2.1	0	Yttrium Y	4.2	0
Natural Graphite C	2.3	0	Iridium Ir	3.2	0	Ruthenium Ru	3.4	1	Ytterbium Yb	6.1	0
Cerium Ce	6.2	1	Lanthanum La	6.0	0	Samarium Sa	6.1	0	Bauxite	2.1	0
Cobalt Co	2.5	1	Lithium Li	1.6	1	Scandium Sc	3.1	0	Coking Coal	1.2	0
Dysprosium Dy	6.2	1	Lutetium Lu	6.1	0	Silicon Si	1.2	1	Fluorspar	1.2	0
Erbium Er	6.1	1	Magnesium Mg	3.9	1	Strontium Sr	2.6	0	Natural Rubber	1.0	0
Europium Eu	3.7	0	Neodymium Nd	6.1	1	Tantalum Ta	1.4	1	Phosphate Rock		0
Gadolinium Gd	6.1	0	Niobium Nb	3.9	0	Terbium Tb	5.5	0			

Appendix D1: Quantum Technologies – Interview and E-mail Communication Summaries

Summary of Interview and E-mail exchange with Expert A for Quantum Communication on Quantum Devices and lower level components on 28th October 2021, 11th November 2021, 27th November 2021, 18th January 2021 and 25th March 2021

Overview on quantum devices

Quantum Devices currently

1. Quantum router & switches
2. Quantum sender
3. Quantum receivers
4. Standard fiber optics cable

Quantum devices future

1. Quantum memories
2. Quantum repeaters

Quantum devices currently – Lower level components

1. Quantum router & switches
    a. Either integrated photonics or MEMS switches
    b. Electronics to control either integrated photonics of MEMS switches
    c. Metal box
    d. Software
2. Quantum sender
    a. Lasers
    b. Telcom modulators (intense, phase) *Lithium niobite* or integrated photonics
    c. Electronics to control
    d. Metal box
    e. Software
    f. For specific quantum sender: quantum dots - Cryogenics, lazers, modulators, software, metal box, specialized material, either *Indium-gallium-arsenide* or *gallium-arsenide*
    g. SPDC (Quantum entanglement sender) *Lithium niobite (PPLN) or barium borate (BBO) or potassium titanium phosphate (KTP)*
3. Quantum receivers
    a. Telecom modulators (possible, not sure)
    b. Software
    c. Metal box
    d. Electronics
    e. Quantum detector: APD, *silicone* or *Indium-gallium-arsenide* or superconducting detectors: Cryogenics, *niobium nitrate or tungsten*.

Quantum devices future – Lower level components

1. Quantum memories
    a. Either integrated photonics or MEMS switches
    b. Electronics to control either integrated photonics of MEMS switches
    c. Metal box
    d. Software
    e. Lasers
    f. Telcom modulators (intense, phase) *Lithium niobite* or integrated photonics
    g. Cryogenics: maybe "helium3"-cryogenics (limited resource) needed. Cryogenics will be needed for sure, but which type is not 100% defined yet.

2. Quantum repeaters
    a. Either integrated photonics or MEMS switches
    b. Electronics to control either integrated photonics of MEMS switches
    c. Metal box
    d. Software
    e. Lasers
    f. Telcom modulators (intense, phase) *Lithium niobite* or integrated photonics

g. For specific quantum sender: quantum dots - Cryogenics, lazers, modulators, software, metal box, specialized material, either *Indium-gallium-arsenide* or *gallium-arsenide*
h. SPDC (Quantum entanglement sender) *Lithium niobite (PPLN) or barium borate (BBO) or potassium titanium phosphate (KTP)*
i. Quantum detector: APD, *silicone* or *Indium-gallium-arsenide* or superconducting detectors: Cryogenics, *niobium nitrate or tungsten*.
j. Cryogenics: maybe “helium3”-cryogenics (limited resource) needed. Cryogenics will be needed for sure, but which type is not 100% defined yet.

Different kinds of technology potentially used within the quantum memories and repeaters (Scenarios for components):

1. Core Technologies (Quantum systems integrated in quantum memories and repeaters):
    a. Diamond-Defect-Centers: e.g. NV Centers
    b. REE-Ion-Crystals:
    c. Single-trapped-ions:
    d. Atomic Clouds:
2. All others above
    a. Senders, routers & switches, receivers
    b. Memories, repeaters
3. Optical cavities: Two mirrors that are highly reflective. So it lets light bounce between each other. They point directly at each other and have special coating on the mirrors.
4. Cryogenic RF-generators (sources): Cryogenics is the field of making refrigerators, that are extremely cold (100K). Different technologies to reach 70K or 4K or below 1K. Quantum techs need to work at 4K or 1K. They are cooling down. Generally commercial, but custom-build. RF = Radio frequency. Generator = generates the radio waves.
5. Superconductor cabling (metal inside of cryostat to be cooled down): Superconductor creates no heat from wiring and makes it possible to direct electricity without losses.
6. Vacuum technology: box made of metal. Remove atmosphere (air) from within the box. Very low air pressure. Super cheap. An opening needs to be there to pump the air out. Opening needs to be precisely made through diamonds or single-use-metals. Vacuum pumps to pump out the air.

General: We need quantum senders, receivers, routers and switches. They are developed today already. For the future there are 4 different technological routes (core technologies above). They however only influence the quantum memories and repeaters. Once the technology is decided, they will be integrated together with the senders, receivers, routers and switches to build the whole quantum technology.

Summary of Interview and E-mail exchange with Expert B for Quantum Technologies on Raw Materials contained in Quantum Devices on 10th February 2021

Quantum Router

For the integrated Photonics, there are three different routes in Quantum Communication to take:

(1) InP Optics or
(2) SiP Optics or
(3) SiN Optics

Additionally for the MEMS switches, they are mostly made from silicone.

Quantum Sender

The **lasers** are based on the same materials as LEDs:

(1) Ga or
(2) GaN

More into detail, the **lasers** are made of … and are light emission

(1) GaP or
(2) GaAs
(3) Diamond based laser (Carbon)

The **telecom modulator** are based on…

(1) LiNb

The **Quantum dots** are based on…

(1) GaAs or
(2) InP

Quantum dots emit particles one at a time (nano-crystals). It needs to be mentioned that cadmium is not used in quantum dots in the quantum communication. It is only used e.g. in PV Solar cells.

Cryogenics are needed for isolation and keeping it cold. There are different ways to build it:

Always used: Cu (lots of). Additionally:

(1) Solid state and liquified gas (little He) and REEs (crystals) as a refrigerator system (new way)
(2) He liquified (old way)

Quantum Receiver

Detector is made of

(1) Ti
(2) Nb (always there, but very small quantities, but heavily dependent on it).
(3) Alloy of Ti and Nb
(4) N
(5) Mo and Si

The old way in research projects were mostly tungsten, but not used anymore.

The detector is dependent on the application but one of the following will be used:

(1) Si used + SiGaAs or
(2) NbN

Summary of Interview with Expert C for Quantum Technologies on Raw Materials contained in Quantum Devices on 19th February 2021

According to Expert C for Quantum Technologies, the goal in quantum communication is to use standard components and not to create new devices. This is in the interest of telecommunication companies, since they want to use old equipment and do not want to replace it.

The following raw material content data were given as part of the interview:

- Quantum Router
    - LiNb
    - Si
- Laser
    - In
    - Ga
    - As
    - P
    - Al
    - Ge
    - Si
- Modulator
    - In
    - P
- Detector
    - In
    - Ga
    - As
    - W
    - Si
    - NbN
- Cryogenics
    - H

Furthermore, there is an upcoming technology called "verschraenkte Photonen", which uses the following new materials

- BBO
- KTP

However, those are employed less, rather Lithium niobite are used.

Lastly, in general the following raw materials are also part of the quantum devices

- Al
- Steel
- Natural Rubber
- Glass
- Au
- Diamond
- Fluor

Summary of Interview with Professor A for Semiconductor and Solid State Physics on Quantum Dots on 18th February 2021

According to Professor A for Semiconductor and Solid State Physics, quantum dots contain the following raw materials:

- Ga
- As
- P
- In
- Al
- Be
- C
- Si

Additionally for the manufacturing machines the following raw materials are needed:

- Ta
- Mo
- W
- Steel
- Au

In general those materials are not used for a fully new kind of technology, but rather current technology such as of a laser is use. In general, those quantum dots have the same semiconductor structures with 10 nano meters as LEDs or laser diodes. The technology behind quantum dots are that electrons are limited to not being able to move and thus produce some kind of energy. For 10 nano meters, this means 10.000 atoms that are acting as a big atom.

In quantum communication, quantum dots use a source for single photons. This means that photons are sent out of quantum dots immediately and to a pre-defined amount. Those are Qbits. Quantum dots are capable of defining the amount of photons sent, which other technologies are not capable of. This is called “Single photons on demand”. Additionally, the security is also of central importance, since in quantum mechanics, photons cannot be “grabbed” during the sending and read. Taking the photons away means destroying them. This makes it more secure to send quantum.

Summary of E-mail exchange with Professor C for Cryogenics on Cryogenics contained in Quantum Technologies on 2nd February 2021 and 15th March 2021

The following information was sent.

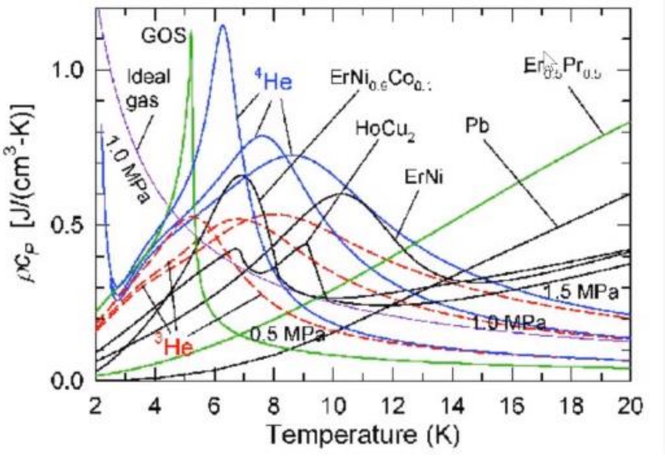
1. Cryocoolers for below 20 K use rare-earth elements (typically 100 gram per cooler) such as erbium and holmium as regenerator material. The number of reliable suppliers of the prepared regenerator materials (small balls of 0.3 mm diameter) is very limited.
2. Dilution refrigerators use 3He as the working fluid. This 3He is a waste product of the hydrogen bomb which uses tritium. Tritium is radioactive and turns into 3He with a half-life time of 10 years. The 3He has to be removed and replaced by tritium. As a result the number of suppliers of 3He is very limited (to the US and Russia?) and the distribution highly political. There have been times where 3He was very hard to get and very expensive. Fortunately, there is an alternative for DR's for cooling to the millikelvins which is adiabatic demagnetization, but quantum-computing researchers seem to prefer DR's.

Additionally, the following list was confirmed to be complete:

- Cu
- GOS
- ErNiCu
- HoCu
- ErNi
- GaP
- Steel
- Plastics
- Bronze
- Pb replacement
- Rubber
- Ag
- Au
- Graphite for the rotor

Summary of the interview with Manufacturer A of Quantum Devices on 12th February 2021

Due to data sharing constraints, solely data was shared that is publicly available on the internet. The data was identified by a ResearchGate search of "Thummes regenerator material" > Pictures. As a citation, the following can be mentioned: Garaway, I & Lewis, M & Bradley, P. & Radebaugh, R. (2011). Measured and Calculated Performance of a High Frequency, 4 K Stage, He-3 Regenerator. Cryocoolers. 16. Additionally, the picture is accessible through the following link https://www.researchgate.net/publication/265990902_Measured_and_Calculated_Performance_of_a_High_Frequency_4_K_Stage_He-3_Regenerator as of 14th June 2021.



The diagram shows the heat capacity and volume temperature. If the curves are going down, this means that the properties decline, which makes it less useful for cryogenics. Furthermore, in order to use cryogenics, it has to be cooled to very low temperatures, between 2,7K and max. 10K. In order to unite these properties, solely the following materials can be potentially used:

- GOS (typical material used): Gandolinium Oxysulfide
- Helium (Working Gas)
- ErNiCo: Erbium Nickel Copper
- HoCu: Holmium Copper
- ErNi: Erbium Nickel

- GaP (also used): Gallium Phosphide

It depends on the manufacturer on which of those materials are used, also combinations of them are possible.

Furthermore, the following materials are included

- Steel
- Cu
- Plastics
- Pb-Replacement
- More common materials
- Bronze
- Natural Rubber

Furthermore, there is a compressor which potentially has the following properties/ materials:

- Au/Ag potentially for semiconductor
- Platine: semiconductor
- Indoor air cooled series

Summary of E-mail exchange with Manufacturer B of Quantum Devices on 15th March 2021

I am able to share some of the materials (though not all) that are of critical importance to us. In particular, we are heavily dependent on cryogenic technologies, so the rare-earth materials used in low-temperature "regenerators" are critical. Specifically: Er, Pr, Dy, as well as superconducting materials such as Nb, Rh, Mo, W, and additives such as Ge and Si. Other materials are used in our cryogenically compatible electrical components such as beryllium and lead that, although not rare, may be restricted in use because of toxicity or environmental impacts, so loss of use of these materials could also impact our ability to produce our products.

Appendix D2: Quantum Technologies - Raw Materials in Equipment

The following Table D2.1 gives an overview on raw materials contained in Quantum devices.

Table D2.1: Raw materials contained in quantum devices.

Quantum Device Current	Lower Level Components	Raw Material Contents
Quantum Router	Integrated Photonics	Al, GaAs, InP, Si, SiP, Si3N4
	MEMS Switches	Si
	Electronics	
	Metal Box	Al alloy
Quantum Sender	Lasers	Al, As, Ga, GaAs, GaN, GaP, Ge, In, P, Si, Synthetic Diamond
	Integrated Photonics	Al, GaAs, InP, Si, Si3N4, SiP
	Modulator	InP, LiNb
	Quantum Dots	Al, As, Be, Ga, GaAs, Graphite, In, InP, P, Si; additionally for the manufacturing: Au, Mo, Steel, Ta, W
	Cryogenics	Ag, Au, Be, Cu, CuSn, Dy, Er, ErNi, ErNiCu, GaP, Ge, Graphite, GOS, H, Ho, HoCu, Mo, Nb, Steel, Pb, Pb replacement, Plastics, Pr, Natural Rubber, Re, Si, W
	Electronics	
	Metal Box	Al alloy
	Modulator	InP, LiNb

Quantum Receiver	Quantum Detector	As, Ga, In, Mo, N, Nb, NbN, Si, Ti, W
	Superconducting Detector	
	Cryogenics	Ag, Au, Be, Cu, CuSn, Dy, Er, ErNi, ErNiCu, GaP, Ge, Graphite, GOS, H, Ho, HoCu, Mo, Nb, Steel, Pb, Pb replacement, Plastics, Pr, Natural Rubber, Re, Si, W
	Integrated Photonics	Al, GaAs, InP, Si, Si3N4, SiP
	Electronics	
	Metal Box	Al alloy

Appendix D3: Quantum Technologies – Supply Risk & Occurrence Assessment

The below Table D3.1 shows the result of the occurrence assessment.

Table D3.1: Occurrence of CRMs in Quantum Technologies Equipment.

	Quantum Router	Quantum Sender	Quantum Receiver	Highest frequently occurring CRMs
Antimony Sb				0
Baryte Ba				0
Beryllium Be		X	X	2
Bismuth Bi				0
Borates B				0
Natural Graphite C		X		1
Cerium Ce				0
Cobalt Co				0
Dysprosium Dy		X	X	2
Erbium Er		X	X	2
Europium Eu				0
Gadolinium Gd		X	X	2
Gallium Ga	X	X	X	3
Germanium Ge		X	X	2
Hafnium Hf				0
Holmium Ho		X	X	2
Indium In	X	X	X	3
Iridium Ir				0
Lanthanum La				0
Lithium Li		X	X	2
Lutetium Lu				0
Magnesium Mg				0
Neodymium Nd				0
Niobium Nb		X	X	2
Palladium Pd				0
Phosphorous P	X	X	X	3
Platinum Pt				0
Praseodymium Pr		X	X	2
Rhodium Rh				0
Ruthenium Ru				0
Samarium Sa				0
Scandium Sc				0
Silicon Si	X	X	X	3
Strontium Sr				0
Tantalum Ta				0
Terbium Tb				0
Thulium Tm				0
Titanium Ti			X	1
Tungsten W		X	X	2
Vanadium V				0
Yttrium Y				0
Ytterbium Yb				0
Bauxite				0
Coking Coal				0
Fluorspar				0
Natural Rubber		X	X	2
Phosphate Rock				0
Total per Technology	4	16	16	

The below Table D3.2 shows the result of the occurrence & supply risk assessment.

Table D3.2: Quantum Technology Criticality Matrix: Occurrence x Supply Risks

	SR	Occ.		SR	Occ.		SR	Occ.		SR	Occ.
Antimony Sb	2.0	0	Gallium Ga	1.3	3	Palladium Pd	1.3	0	Thulium Tm	6.1	0

Baryte Ba	1.3	0	Germanium Ge	3.9	2	Phosphorous P	3.5	3	Titanium Ti	1.3	1
Beryllium Be	2.3	2	Hafnium Hf	1.1	0	Platinum Pt	1.8	0	Tungsten W	1.6	2
Bismuth Bi	2.2	0	Holmium Ho	6.1	2	Praseodymium Pr	5.5	2	Vanadium V	1.7	0
Borates B	3.2	0	Indium In	1.8	3	Rhodium Rh	2.1	0	Yttrium Y	4.2	0
Natural Graphite C	2.3	1	Iridium Ir	3.2	0	Ruthenium Ru	3.4	0	Ytterbium Yb	6.1	0
Cerium Ce	6.2	0	Lanthanum La	6.0	0	Samarium Sa	6.1	0	Bauxite	2.1	0
Cobalt Co	2.5	0	Lithium Li	1.6	2	Scandium Sc	3.1	0	Coking Coal	1.2	0
Dysprosium Dy	6.2	2	Lutetium Lu	6.1	0	Silicon Si	1.2	3	Fluorspar	1.2	0
Erbium Er	6.1	2	Magnesium Mg	3.9	0	Strontium Sr	2.6	0	Natural Rubber	1.0	2
Europium Eu	3.7	0	Neodymium Nd	6.1	0	Tantalum Ta	1.4	0	Phosphate Rock		0
Gadolinium Gd	6.1	2	Niobium Nb	3.9	2	Terbium Tb	5.5	0			

Below Figure D3.1 – D3.3 represent the results of the supply risk assessment of CRMs contained in Quantum devices.

Quantum Router

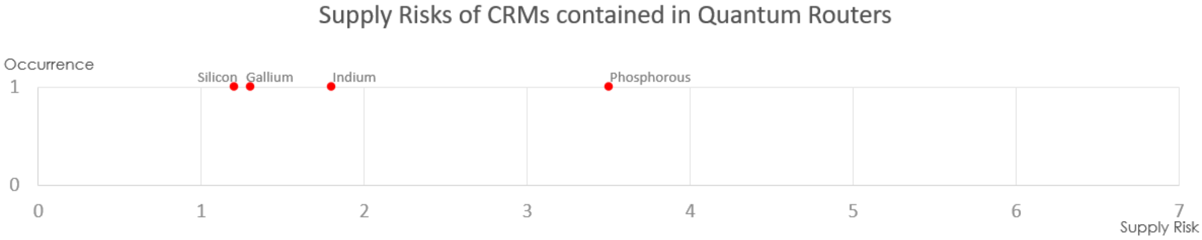


Figure D3.1: Supply Risks of CRMs contained in Quantum Routers.

Looking at the CRMs contained in Quantum Routers, relatively low supply risks can be identified. Solely Phosphorous causes a rather moderate supply risk on the development and implementation of the device. Phosphorous is solely contained in the lower level component of Integrated Photonics.

Quantum Sender

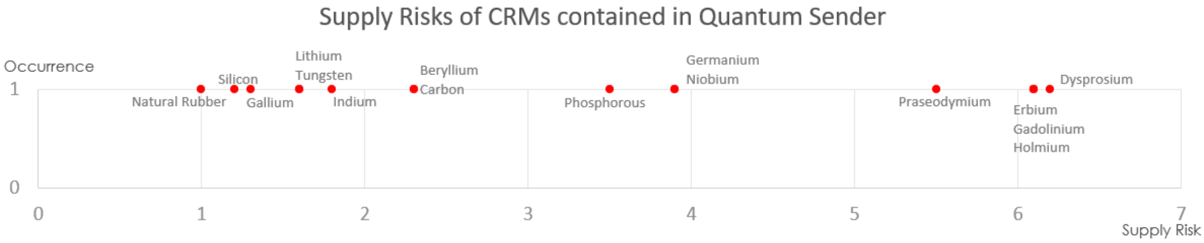


Figure D3.2: Supply Risks of CRMs contained in Quantum Senders.

In the case of a Quantum Sender, five CRMs are associated with major supply risks. Those include Dy, Er, Gad, Ho and Pr. Additionally, three CRMs, Ge, Nb and P, are of moderate supply risk. Looking at the lower level components, especially Cryogenics impose a supply risk. All the highly risky CRMs are contained in a Cryocooler.

Quantum Receiver

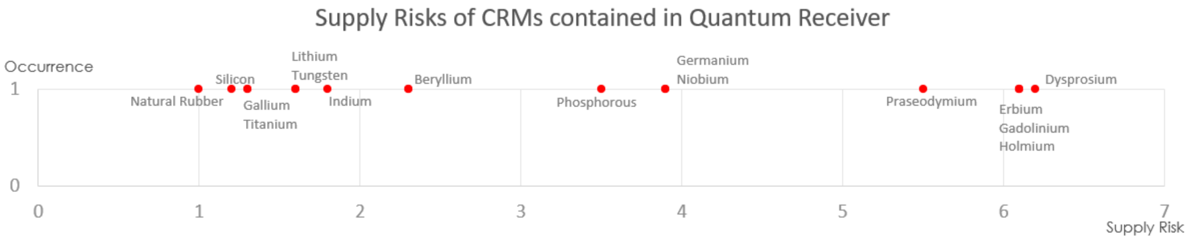


Figure D.3.3: Supply Risks of CRMs contained in Quantum Receivers.

Compared to the Quantum Sender as above, the same holds true for the Quantum Receiver. However, a Quantum Receiver also contains Ti, which is of rather low risk. Again, the Cryogenics lower level component is associated with the highest supply risks.

Appendix E1: Future Telecommunication Technologies – Supply Risk & Occurrence Assessment

The below Table E1.1 gives a summary on all CRMs contained in different future technologies in the telecommunication industry.

Table E1.1: Occurrence analysis of CRMs contained in the four focus future technologies.

	5G	Photonics	Edge Computing	Quantum Technologies	Highest frequently occurring CRMs
Antimony Sb	X		X		2
Baryte Ba	X	X			2
Beryllium Be	X			X	2
Bismuth Bi	X	X			2
Borates B	X		X		2
Natural Graphite C	X			X	2
Cerium Ce	X		X		2
Cobalt Co	X	X	X		3
Dysprosium Dy	X		X	X	3
Erbium Er	X	X	X	X	4
Europium Eu	X				1
Gadolinium Gd	X			X	2
Gallium Ga	X	X	X	X	4
Germanium Ge	X	X	X	X	4
Hafnium Hf	X				1
Holmium Ho	X			X	2
Indium In	X	X			2
Iridium Ir	X			X	2
Lanthanum La	X				1
Lithium Li		X	X	X	3
Lutetium Lu	X				1
Magnesium Mg	X	X	X		3
Neodymium Nd	X		X		2
Niobium Nb	X	X		X	3
Palladium Pd	X	X	X		3
Phosphorous P	X	X	X	X	4
Platinum Pt	X	X			2
Praseodymium Pr	X	X		X	3
Rhodium Rh	X				1
Ruthenium Ru	X		X		2
Samarium Sa	X				1
Scandium Sc	X				1
Silicon Si	X	X	X	X	4
Strontium Sr	X				1
Tantalum Ta	X	X	X		3
Terbium Tb	X				1
Thulium Tm	X				1
Titanium Ti	X	X	X	X	4
Tungsten W	X		X	X	3
Vanadium V	X				1
Yttrium Y	X				1
Ytterbium Yb	X	X			2
Bauxite					0
Coking Coal					0
Fluorspar					0
Natural Rubber	X			X	2
Phosphate Rock					0
Total per Technology	39	18	17	16	

Table E1.2: Summary of supply risk and occurrence data for each of the identified CRMs.

	SR	**Occ.**		**SR**	**Occ.**		**SR**	**Occ.**		**SR**	**Occ.**
Antimony Sb	2.0	2	Gallium Ga	1.3	4	Palladium Pd	1.3	3	Thulium Tm	6.1	1
Baryte Ba	1.3	2	Germanium Ge	3.9	4	Phosphorous P	3.5	4	Titanium Ti	1.3	4
Beryllium Be	2.3	2	Hafnium Hf	1.1	1	Platinum Pt	1.8	2	Tungsten W	1.6	3
Bismuth Bi	2.2	2	Holmium Ho	6.1	2	Praseodymium Pr	5.5	3	Vanadium V	1.7	1
Borates B	3.2	2	Indium In	1.8	2	Rhodium Rh	2.1	1	Yttrium Y	4.2	1
Natural Graphite C	2.3	2	Iridium Ir	3.2	2	Ruthenium Ru	3.4	2	Ytterbium Yb	6.1	2
Cerium Ce	6.2	2	Lanthanum La	6.0	1	Samarium Sa	6.1	1	Bauxite	2.1	0
Cobalt Co	2.5	3	Lithium Li	1.6	3	Scandium Sc	3.1	1	Coking Coal	1.2	0
Dysprosium Dy	6.2	3	Lutetium Lu	6.1	1	Silicon Si	1.2	4	Fluorspar	1.2	0
Erbium Er	6.1	4	Magnesium Mg	3.9	3	Strontium Sr	2.6	1	Natural Rubber	1.0	2
Europium Eu	3.7	1	Neodymium Nd	6.1	2	Tantalum Ta	1.4	3	Phosphate Rock		0
Gadolinium Gd	6.1	2	Niobium Nb	3.9	3	Terbium Tb	5.5	1			

Appendix Chapter 5 – Critical Raw Material Demand Scenarios

CRM Weights Data Gathering Process

The first step of the pre-assessment included a review of the data gathering process. The weights data gathering process varied across technologies. For some technologies it went together with the gathering of CRMs contained in future equipment of the first research question and for some additional steps were required. Furthermore, depending on the expected implementation timeline of the technologies it was easier or more difficult to retrieve data. Due to the fact that 5G and Edge Computing Servers already exist in the market, it was more challenging to gain data, due to competitive advantages of suppliers. For 5G, several rounds of discussions were conducted and rather high-level data was shared. For Edge Computing, data on a server was immediately shared. Data on this server however mainly represents a standard server, but is a good indication for an Edge Computing Server as well. In the case of Photonics and Quantum Technologies, contrarily it was easier to gather data. Those technologies are not widely rolled out yet and are rather in the development stage. Thus, retrieved data comes mainly from research institutes, which were more willing to share their research publicly. For Photonics, data on transceivers and amplifiers could be gathered, coming from research institutes, as well as suppliers. For Quantum Technologies, data retrieved came from research institutes. Expert A on Quantum Communication (2021) established an internal working group to estimate the amounts of materials contained in Quantum devices together with several experts in the field and shared averages numbers to which all experts could agree on.

Appendix F: Pre-Assessment – CRM Weights Data Availability

The first step of the pre-assessment included a visual inspection of the available weights data. Not for all the before defined equipment, weights data could be found. The below Table F.1 gives an overview on which data could be gathered and which could not.

Table F.1: CRM weight data availability of future equipment part of the selected future technologies.

	5G				Photonics			Edge Computing	Quantum Technologies		
	RAN	Mobile	RRU	Antenna	Transceiver	Amplifier	Optical Switch	Server	Router	Sender	Receiver
Antimony Sb	No data	No data	X				No data	X			
Baryte Ba	No data	No data	X				No data				
Beryllium Be	No data	No data	X				No data			X	X
Bismuth Bi	No data	No data	X		X	X	No data	X			
Borates B	No data	No data	X				No data				
Carbon C	No data	No data	X	X			No data			X	
Cerium Ce	No data	No data					No data				
Cobalt Co	No data	No data	X				No data	X			
Dysprosium Dy	No data	No data					No data	X		X	X
Erbium Er	No data	No data				X	No data	X		X	X
Europium Eu	No data	No data					No data				
Gadolinium Gd	No data	No data					No data			No data	No data
Gallium Ga	No data	No data	X		X		No data	X	X	X	X
Germanium Ge	No data	No data			X	X	No data	X		X	X
Hafnium Hf	No data	No data					No data				
Holmium Ho	No data	No data					No data			X	X
Indium In	No data	No data	X		X		No data		X	X	X
Iridium Ir	No data	No data					No data				
Lanthanum La	No data	No data					No data				
Lithium Li	No data	No data					No data	X		X	X
Lutetium Lu	No data	No data					No data				
Magnesium Mg	No data	No data	X	X	X		No data	X			
Neodymium Nd	No data	No data	X				No data	X			
Niobium Nb	No data	No data	X				No data			X	X
Palladium Pd	No data	No data	X		X	X	No data	X			
Phosphorous P	No data	No data	X		X		No data	X	X	X	X
Platinum Pt	No data	No data	X		X		No data				
Praseodymium Pr	No data	No data				X	No data			X	X
Rhodium Rh	No data	No data					No data				
Ruthenium Ru	No data	No data	X				No data	X			

Samarium Sa	No data	No data	X				No data				
Scandium Sc	No data	No data					No data				
Silicon Si	No data	No data	X	X	X	X	No data	X	X	X	X
Strontium Sr	No data	No data	X				No data				
Tantalum Ta	No data	No data	X				No data	X			
Terbium Tb	No data	No data	X				No data				
Thulium Tm	No data	No data				X	No data				
Titanium Ti	No data	No data	X		X		No data				X
Tungsten W	No data	No data	X				No data	X		X	X
Vanadium V	No data	No data	X				No data				
Yttrium Y	No data	No data	X				No data				
Ytterbium Yb	No data	No data					No data				
Bauxite	No data	No data					No data				
Coking Coal	No data	No data					No data				
Fluorspar	No data	No data					No data				
Natural Rubber	No data	No data	X				No data			X	X

Appendix G: 5G Technology – Critical Raw Material Demand Development

Slow rollout of 5G Technologies until 2030

The following global connections were identified.

Table G.1: Development of global connections covered by 5G according to GSMA (2020) and estimated.

Scenario	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Slow rollout scenario	6%	9%	12%	16%	20%	25%	30%	36%	42%	49%

Based on the global 5G connections, the base stations per square km and the global settlement area, calculations were conducted. The first step was to calculate the globally covered square kilometers, based on the percentages mentioned in the main text.

$$Square\ km\ covered\ with\ 5G\ globally\ 2021 = 19.500.000\ km^2\ x\ 6\% = 1.170.000\ km^2$$

In order to serve an area of 2.925.000km^2, the following amount of base stations will be needed.

$$Amount\ of\ 5G\ base\ stations\ in\ 2021 = 1.170.000\ km^2 * 50 \frac{Base\ stations}{km^2} = 58{,}50\ million\ 5G\ base\ stations$$

These amount of base stations would require the following amount of RRUs and antennas.

$$Amount\ of\ RRUs\ globally\ in\ 2021 = 58{,}50\ million\ \ x\ 2\ RRUs = 117\ million\ RRUs$$

$$Amount\ of\ antennas\ globally\ until\ 2021 = 58{,}50\ million\ x\ 3\ antennas = 175{,}5\ million\ antennas$$

These calculations resulted in the following device developments as shown in Table G.2.

Table G.2: Amount of 5G base stations, RRUs and antennas under a slow rollout scenario for 5G Technologies.

In Billion	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
5G Base Stations	0,06	0,09	0,12	0,16	0,2	0,24	0,29	0,35	0,41	0,48
5G RRUs	0,12	0,18	0,24	0,32	0,4	0,48	0,58	0,70	0,82	0,96
5G Antennas	0,18	0,27	0,36	0,48	0,60	0,72	0,87	1,05	1,23	1,44

Below Table G.3 shows the demand development of CRMs for the 5G RRU until 2030 under a slow rollout scenario, scaled up according to the 5G global connections.

Table G.3: Development of CRMs contained in 5G Remote Radio Unit until 2030 under a slow rollout scenario.

	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Antimony Sb	959,75	1.439,63	1.919,5	2.559,34	3.199,17	3.998,96	4.798,76	5.758,51	6.718,26	7.837,97
Borates B	28,08	42,12	56,16	74,88	93,6	117	140,4	168,48	196,56	229,32
Baryte Ba	10.331,45	15.497,18	20.662,9	27.550,54	34.438,17	43.047,71	51.657,26	61.988,71	72.320,16	84.373,52
Beryllium Be	135,02	202,53	270,04	360,05	450,06	562,58	675,09	810,12	945,13	1.102,65
Bismuth Bi	640,69	961,04	1.281,38	1.708,51	2.135,64	2.669,55	3.203,46	3.844,15	4.484,84	5.232,32
Graphite C	1.206,97	1.810,46	2.413,94	3.218,59	4.023,24	5.029,05	6.034,86	7.241,83	8.448,8	9.856,94
Cobalt Co	28,43	42,65	56,86	75,82	94,77	118,46	142,16	170,59	199,02	232,19
Gallium Ga	10,53	15,80	21,06	28,08	35,1	43,88	52,65	63,18	73,71	86
Indium In	5,15	7,72	10,30	13,73	17,16	21,45	25,74	30,89	36,04	42,04
Magnesium Mg	90.055,37	135.083,1	180.110,7	240.147,6	300.184,6	375.230,7	450.276,8	540.332,2	630.387,6	735.452,2
Neodymium Nd	26,56	39,84	53,12	70,82	88,53	110,66	132,80	159,35	185,91	216,9
Niobium Nb	0	0	0,001	0,001	0,001	0,001	0,001	0,001	0,002	0,002
Phosphorous P	313,44	470,17	626,89	835,85	1.044,81	1.306,01	1.567,22	1.880,66	2.194,10	2.559,79
Palladium Pd	49,49	74,24	98,98	131,98	164,97	206,21	247,46	296,95	346,44	404,18
Platinum Pt	2,46	3,69	4,91	6,55	8,19	10,24	12,29	14,74	17,2	20,1
Ruthenium Ru	1,99	2,98	3,98	5,3	6,63	8,29	9,95	11,93	13,92	16,24
Silicon Si	225.784,6	338.676,9	451.569,2	602.092,3	752.615,4	940.769,2	1.128.923	1.354.708	1.580.492	1.843.908
Samarium Sm	0,04	0,05	0,07	0,09	0,12	0,15	0,18	0,21	0,25	0,29
Strontium Sr	2.078,97	3.118,46	4.157,95	5.543,93	6.929,91	8.662,39	10.394,87	12.473,84	14.552,81	16.978,28
Tantalum Ta	87,28	130,92	174,56	232,75	290,94	363,68	436,41	523,69	610,97	712,8
Terbium Tb	1,76	2,63	3,51	4,68	5,85	7,31	8,78	10,53	12,29	14,33
Titanium Ti	20.313,07	30.469,61	40.626,14	54.168,19	67.710,24	84.637,8	101.565,4	121.878,4	142.191,5	165.890,1
Tungsten W	1,64	2,46	3,28	4,37	5,46	6,83	8,19	9,83	11,47	13,38
Vanadium V	0,004	0,005	0,007	0,009	0,01	0,01	0,02	0,02	0,02	0,03
Yttrium Y	1563,00	2.344,51	3.126,01	4.168,01	5.210,01	6.512,51	7.815,02	9.378,02	10.941,02	12.764,52
Natural Rubber	1,4	2,11	2,81	3,74	4,68	5,85	7,02	8,42	9,83	11,47

Below Table G.4 shows the demand development of CRMs for the 5G Antenna until 2030 under a slow rollout scenario.

Table G.4: Development of CRMs contained in 5G Antenna until 2030 under a slow rollout scenario.

Weight per CRM		Development over time in million tons									
CRM	**Weight (g)**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Graphite C	4245	0,74	1,12	1,49	1,99	2,48	3,1	3,72	4,47	5,21	6,08
Magnesium Mg	1245	0,22	0,32	0,44	0,58	0,73	0,91	1,09	1,31	1,53	1,78
Silicon Si	572	0,11	0,16	0,21	0,28	0,35	0,44	0,53	0,64	0,74	0,87

Below Table G.5 shows the demand development of CRMs for all 5G devices until 2030 under a slow rollout scenario.

Table G.5: Development of CRMs contained in 5G Devices until 2030 under a slow rollout scenario.

In Tons	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Antimony Sb	959,751	1439,627	1919,502	2559,336	3199,17	3998,9625	4798,755	5758,506	6718,257	7837,967
Borates B	28,08	42,12	56,16	74,88	93,6	117	140,4	168,48	196,56	229,32
BaryteBa	10331,45	15497,18	20662,9	27550,54	34438,17	43047,7125	51657,26	61988,71	72320,16	84373,52
Beryllium Be	135,018	202,527	270,036	360,048	450,06	562,575	675,09	810,108	945,126	1102,647
Bismuth Bi	640,692	961,038	1281,384	1708,512	2135,64	2669,55	3203,46	3844,152	4484,844	5232,318
Graphite C	746204,5	1119307	1492409	1989879	2487348	3109185,3	3731022	4477227	5223431	6094003
Cobalt Co	28,431	42,6465	56,862	75,816	94,77	118,4625	142,155	170,586	199,017	232,1865
Gallium Ga	10,53	15,795	21,06	28,08	35,1	43,875	52,65	63,18	73,71	85,995
Indium In	5,148	7,722	10,296	13,728	17,16	21,45	25,74	30,888	36,036	42,042
Magnesium Mg	308552,9	462829,3	617105,7	822807,6	1028510	1285636,95	1542764	1851317	2159870	2519848
Neodymium Nd	26,559	39,8385	53,118	70,824	88,53	110,6625	132,795	159,354	185,913	216,8985
Niobium Nb	0,000236	0,000355	0,000473	0,00063	0,000788	0,00098475	0,001182	0,001418	0,001654	0,00193
Phosphorous P	313,443	470,1645	626,886	835,848	1044,81	1306,0125	1567,215	1880,658	2194,101	2559,785
Palladium Pd	49,491	74,2365	98,982	131,976	164,97	206,2125	247,455	296,946	346,437	404,1765
Platinum Pt	2,457	3,6855	4,914	6,552	8,19	10,2375	12,285	14,742	17,199	20,0655
Ruthenium Ru	1,989	2,9835	3,978	5,304	6,63	8,2875	9,945	11,934	13,923	16,2435
Silicon Si	326170,6	489255,9	652341,2	869788,3	1087235	1359044,21	1630853	1957024	2283194	2663727
Samarium Sm	0,035411	0,053117	0,070822	0,09443	0,118037	0,14754675	0,177056	0,212467	0,247879	0,289192
Strontium Sr	2078,973	3118,46	4157,946	5543,928	6929,91	8662,3875	10394,87	12473,84	14552,81	16978,28
Tantalum Ta	87,282	130,923	174,564	232,752	290,94	363,675	436,41	523,692	610,974	712,803
Terbium Tb	1,755	2,6325	3,51	4,68	5,85	7,3125	8,775	10,53	12,285	14,3325
Titanium Ti	20313,07	30469,61	40626,14	54168,19	67710,24	84637,8	101565,4	121878,4	142191,5	165890,1
Tungsten W	1,638	2,457	3,276	4,368	5,46	6,825	8,19	9,828	11,466	13,377
Vanadium V	0,00351	0,005265	0,00702	0,00936	0,0117	0,014625	0,01755	0,02106	0,02457	0,028665
Yttrium Y	1563,003	2344,505	3126,006	4168,008	5210,01	6512,5125	7815,015	9378,018	10941,02	12764,52
Natural Rubber	1,404	2,106	2,808	3,744	4,68	5,85	7,02	8,424	9,828	11,466

Below Figure G.1 – G.5 shows the demand development of CRMs per 5G device and aggregated.

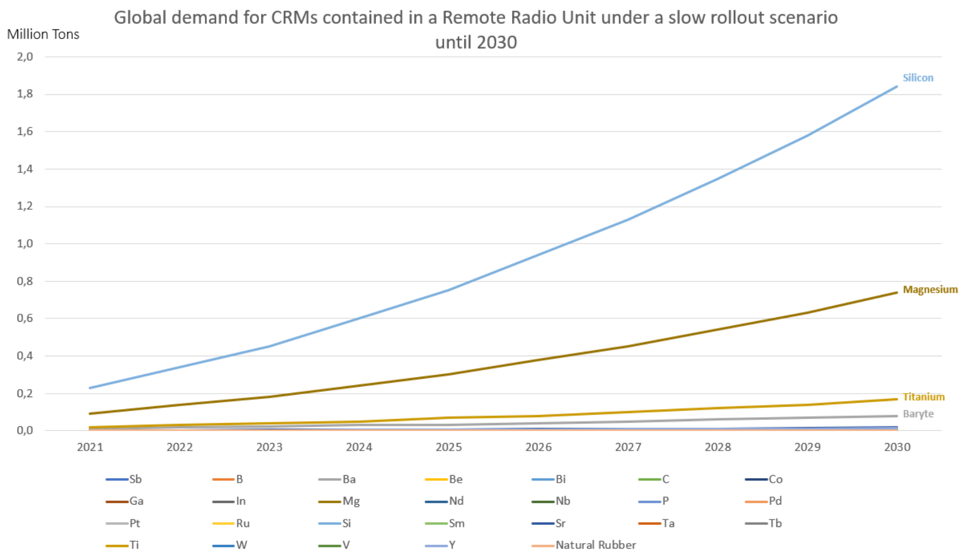


Figure G.1: Demand development of CRMs contained in a Remote Radio Unit under a slow rollout scenario until 2030.

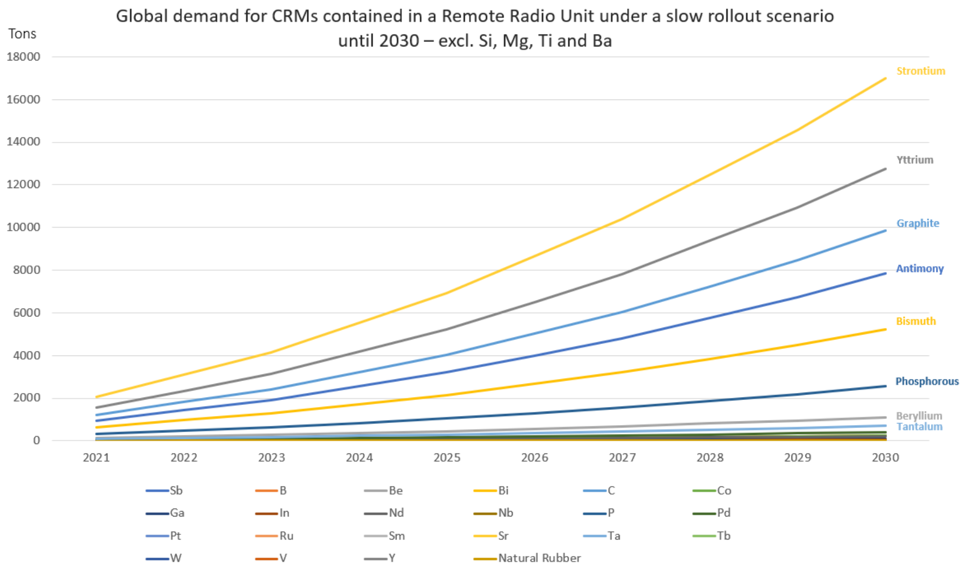


Figure G.2: Demand development of CRMs contained in a Remote Radio Unit under a slow rollout scenario until 2030 – Excluding Si, Mg, Ti and Ba.

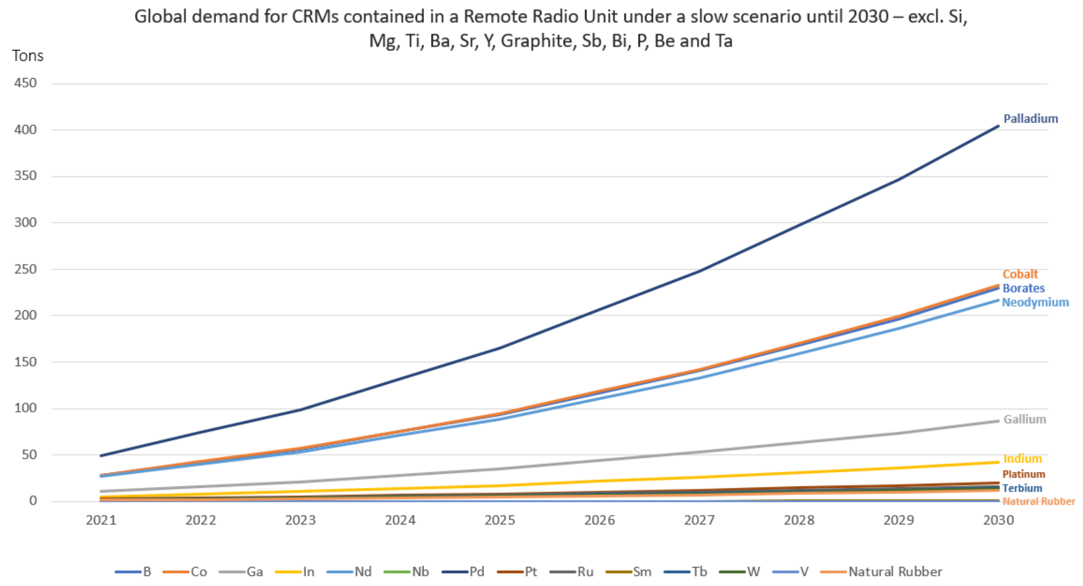


Figure G.3: Demand development of CRMs contained in a Remote Radio Unit under a slow rollout scenario until 2030 – Excluding Si, Mg, Ti, Ba, Sr, Y, Graphite, Sb, Bi, P, Be and Ta.

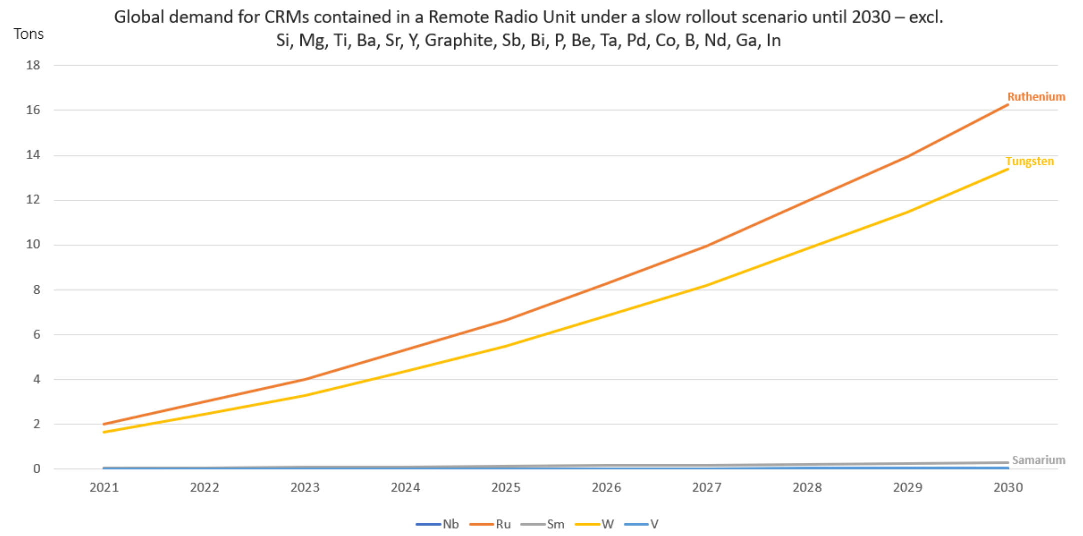


Figure G.4: Demand development of CRMs contained in a Remote Radio Unit under a slow rollout scenario until 2030 – Excluding Si, Mg, Ti, Ba, Sr, Y, Graphite, Sb, Bi, P, Be, Ta, Pd, Co, B, Nd, Ga, In, Pt, Tb and Natural Rubber.

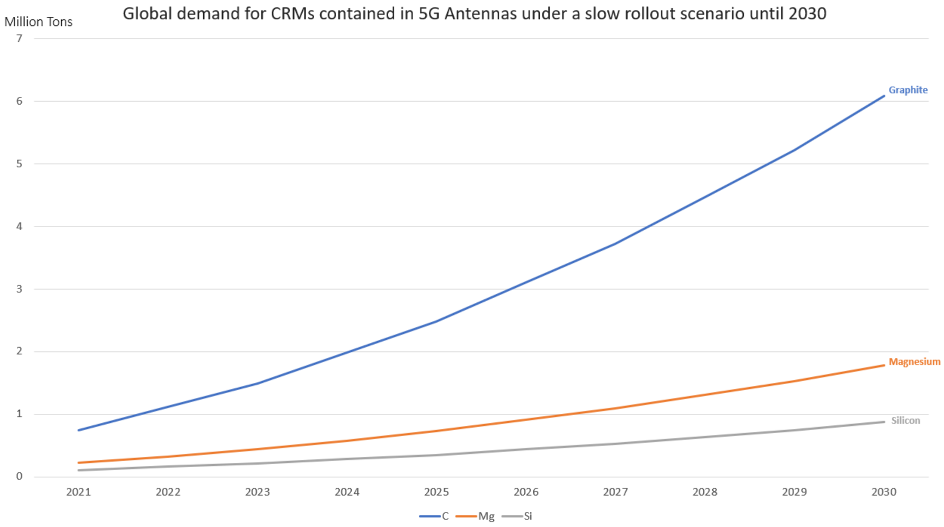


Figure G.5: Demand development of CRMs contained in an Antenna under a slow rollout scenario until 2030.

Below, the CRM demand development aggregated for all 5G devices under a slow rollout scenario are represented in Figure G.6 – G.9.

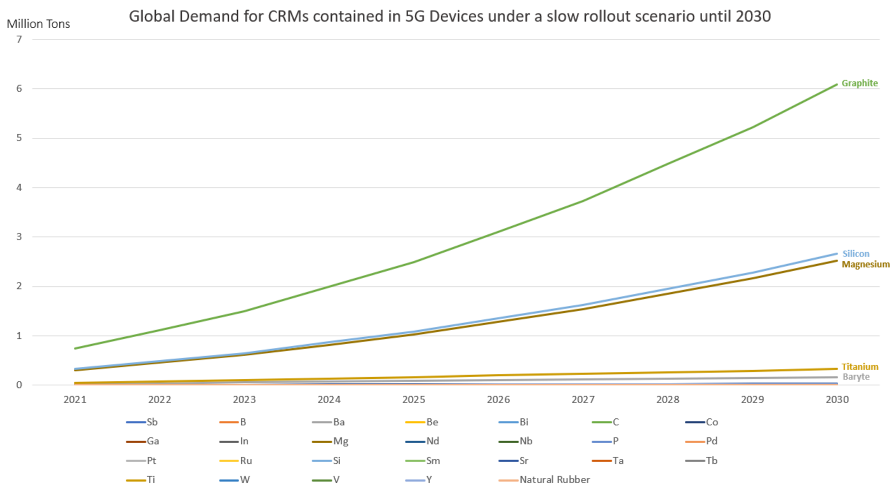


Figure G.6: Demand development of CRMs contained in 5G Devices under a slow rollout scenario until 2030.

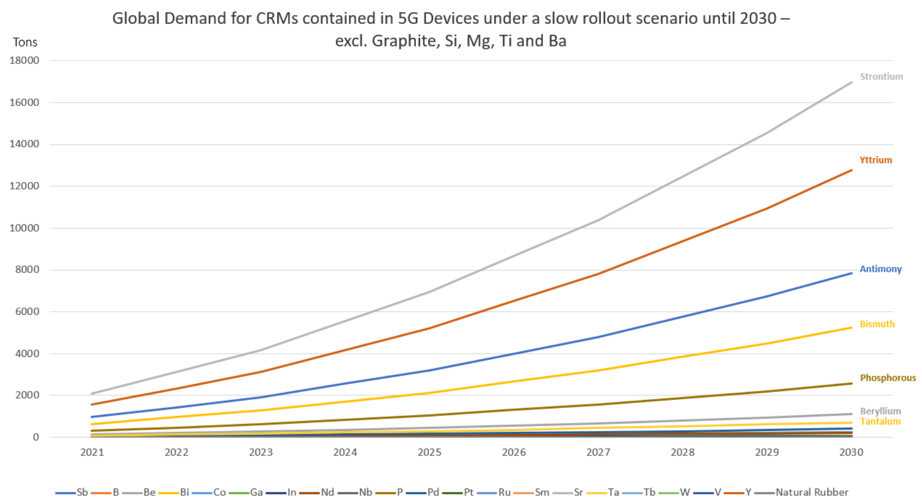


Figure G.7: Demand development of CRMs contained in 5G Devices under a slow rollout scenario until 2030 – Excluding Graphite, Si, Mg, Ti and Ba.

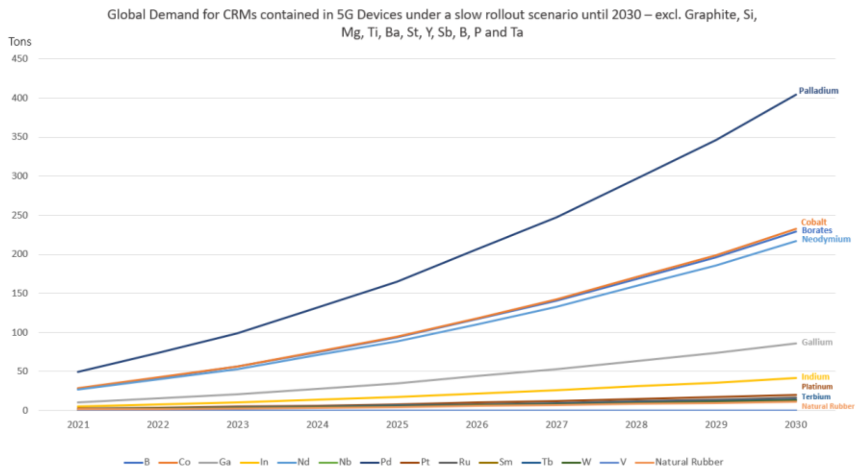


Figure G.8: Demand development of CRMs contained in 5G Devices under a slow rollout scenario until 2030 – Excluding Graphite, Si, Mg, Ti, Ba, Sr, Y, Sb, Bi, P and Ta.

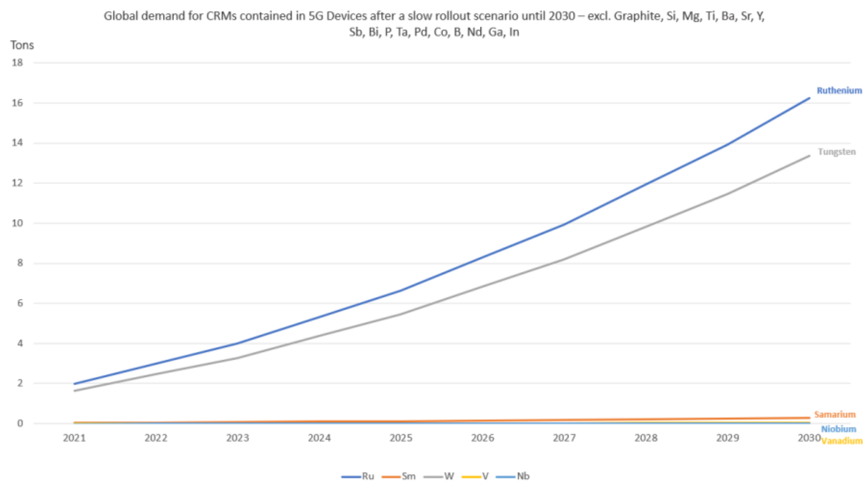


Figure G.9: Demand development of CRMs contained in 5G Devices under a slow rollout scenario until 2030 – Excluding Graphite, Si, Mg, Ti, Ba, Sr, Y, Sb, Bi, P, Ta, Pd, Co, B, Nd, Ga, In, Pt, Tb and Natural Rubber.

Fast rollout scenario of 5G Technologies until 2030

The following 5G connections percentages were identified.

Table G.6: Development of global connections covered by 5G according to GSMA (2020) and estimated.

Scenario	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Fast rollout scenario	15%	24%	33%	42%	51%	60%	69%	78%	87%	96%

The same calculations as above were made based on the percentages of global 5G connections until 2030. The following shows the made calculations.

$$Square\ km\ covered\ with\ 5G\ globally = 19.500.000\ km^2\ x\ 15\% = 2.925.000\ km^2$$

In order to serve an area of 2.925.000km^2, the following amount of base stations will be needed.

$$Amount\ of\ 5G\ base\ stations\ in\ 2021 = 2.935.000\ km^2 * 50 \frac{Base\ stations}{km^2} = 146{,}75\ million\ 5G\ base\ stations$$

These amount of base stations would require the following amount of RRUs and antennas.

$$Amount\ of\ RRUs\ globally\ in\ 2021 = \ 146{,}75\ million\ \ x\ 2\ RRUs = 293{,}5\ million\ RRUs$$

$$Amount\ of\ antennas\ globally\ until\ 2021 = 146{,}75\ million\ x\ 3\ antennas = 440{,}25\ million\ antennas$$

These amount of 5G devices were taken and scaled up until 2030 according to the numbers retrieved from Ericsson (2020) and can be found in the following Table G.7.

Table G.7: Amount of 5G base stations, RRUs and antennas under Scenario 2 for 5G Technologies.

In Billion	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
5G Base Stations	0,15	0,23	0,32	0,41	0,50	0,59	0,67	0,76	0,85	0,94
5G RRUs	0,29	0,47	0,64	0,82	1,00	1,17	1,35	1,52	1,7	1,87
5G Antennas	0,44	0,70	0,97	1,23	1,50	1,76	2,02	2,28	2,54	2,82

Below Table G.8 shows the demand development of CRMs for the 5G RRU until 2030 under a fast rollout scenario.

Table G.8: Development of CRMs contained in 5G Remote Radio Unit until 2030 under a fast rollout scenario.

In tons	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Antimony Sb	2.399,38	3.839,00	5.278,63	6.718,26	8.157,88	9.597,51	11.037,14	12.476,76	13.916,39	15.356,02
Boron B	70,2	112,32	154,44	196,56	238,68	280,8	322,92	365,04	407,16	449,28
Barium Ba	25.828,63	41.325,8	56.822,98	72.320,16	87.817,33	103.314,5	118.811,7	134.308,9	149.806	165.303,2
Beryllium Be	337,55	540,07	742,60	945,13	1.147,65	1.350,18	1.552,71	1.755,23	1.957,76	2.160,29
Bismuth Bi	1.601,73	2.562,77	3.523,81	4.484,84	5.445,88	6.406,92	7.367,96	8.329	9.290,03	10.251,07
Graphite C	3.017,43	4.827,89	6.638,35	8.448,80	10.259,26	12.069,72	13.880,18	15.690,64	17.501,09	19.311,55
Cobalt Co	71,08	113,72	156,37	199,02	241,66	284,31	326,96	369,60	412,25	454,90
Gallium Ga	26,33	42,12	57,92	73,71	89,51	105,3	121,10	136,89	152,69	168,48
Indium In	12,87	20,59	28,31	36,04	43,76	51,48	59,20	66,92	74,65	82,37
Magnesium Mg	225.138,4	360.221,5	495.304,5	630.387,6	765.470,6	900.553,7	1.035.637	1.170.720	1.305.803	1.440.886
Neodymium Nd	66,40	106,24	146,07	185,91	225,75	265,59	305,43	345,27	385,12	424,94
Niobium Nb	0,001	0,001	0,001	0,002	0,002	0,002	0,003	0,003	0,0034	0,004
Phosphorous P	783,61	1.253,77	1.723,94	2.194,1	2.664,27	3.134,43	3604,60	4.074,76	4.544,92	5015,1
Palladium Pd	123,73	197,96	272,20	346,44	420,67	494,91	569,15	643,38	717,62	791,86
Platinum Pt	6,14	9,83	13,51	17,20	20,88	24,57	28,26	31,94	35,63	39,31
Ruthenium Ru	4,97	7,96	10,94	13,92	16,91	19,89	22,87	25,86	28,84	31,82
Silicon Si	564.461,5	903.138,4	1.241.815	1.580.492	1.919.169	2.257.846	2.596.523	2.935.200	3.273.877	3.612.554
Samarium Sm	0,09	0,14	0,20	0,25	0,30	0,35	0,41	0,46	0,51	0,57
Strontium Sr	5.197,43	8.315,89	11.434,35	14.552,81	17.671,27	20.789,73	23.908,19	27.026,65	30.145,11	33.263,57
Tantalum Ta	218,21	349,13	480,05	610,97	741,90	872,82	1.003,74	1.134,67	1.265,59	1.396,51
Terbium Tb	4,39	7,02	9,65	12,29	14,92	17,55	20,18	22,82	25,45	28,08
Titanium Ti	50.782,68	81.252,29	111.721,9	142.191,5	172.661,1	203.130,7	233.600,3	264.069,9	294.539,5	325.009,2
Tungsten W	4,1	6,55	9,01	11,47	13,92	16,38	18,84	21,29	23,75	26,21
Vanadium V	0,009	0,01	0,02	0,03	0,03	0,04	0,04	0,05	0,05	0,06
Yttrium Y	3.907,51	6.252,01	8.596,52	10.941,02	13.285,53	15.630,03	17.974,53	20.319,04	22.663,54	25.008,05
Natural Rubber	3,51	5,62	7,72	9,83	11,93	14,04	16,15	18,25	20,36	22,46

Below Table G.9 shows the demand development of CRMs for the 5G Antenna until 2030 under a fast rollout scenario.

Table G.9: Development of CRMs contained in 5G Antenna until 2030 under a fast rollout scenario.

Weight per CRM		Development over time in million tons									
CRM	**Weight (g)**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Graphite C	4245	1,86	2,98	4,1	5,21	6,33	7,45	8,57	9,68	10,8	11,92
Magnesium Mg	1245	0,55	0,87	1,20	1,53	1,86	2,18	2,51	2,84	3,17	3,5
Silicon Si	572	0,25	0,4	0,55	0,7	0,85	1	1,15	1,31	1,46	1,61

Below Table G.10 shows the demand development of CRMs for the 5G devices until 2030 under a fast rollout scenario.

Table G.10: Development of CRMs contained in 5G Devices until 2030 under a fast rollout scenario.

In Tons	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Antimony Sb	2.399,38	3.839,00	5.278,63	6.718,26	8.157,88	9.597,51	11.037,14	12.476,76	13.916,39	15.356,02
Boron B	70,2	112,32	154,44	196,56	238,68	280,8	322,92	365,04	407,16	449,28
Barium Ba	25.828,63	41.325,8	56.822,98	72.320,16	87.817,33	103.314,5	118.811,7	134.308,9	149.806	165.303,2
Beryllium Be	337,55	540,07	742,60	945,13	1.147,65	1.350,18	1.552,71	1.755,23	1.957,76	2.160,29
Bismuth Bi	1.601,73	2.562,77	3.523,81	4.484,84	5.445,88	6.406,92	7.367,96	8.329	9.290,03	10.251,07
Graphite C	1865511	2984818	4104125	5223431	6342738	7462045	8581351	9700658	10819965	11939272
Cobalt Co	71,08	113,72	156,37	199,02	241,66	284,31	326,96	369,60	412,25	454,90
Gallium Ga	26,33	42,12	57,92	73,71	89,51	105,3	121,10	136,89	152,69	168,48
Indium In	12,87	20,59	28,31	36,04	43,76	51,48	59,20	66,92	74,65	82,37
Magnesium Mg	771382,2	1234211	1697041	2159870	2622699	3085529	3548358	4011187	4474017	4936846
Neodymium Nd	66,40	106,24	146,07	185,91	225,75	265,59	305,43	345,27	385,12	424,94
Niobium Nb	0,001	0,001	0,001	0,002	0,002	0,002	0,003	0,003	0,0034	0,004
Phosphorous P	783,61	1.253,77	1.723,94	2.194,1	2.664,27	3.134,43	3604,60	4.074,76	4.544,92	5015,1
Palladium Pd	123,73	197,96	272,20	346,44	420,67	494,91	569,15	643,38	717,62	791,86
Platinum Pt	6,14	9,83	13,51	17,20	20,88	24,57	28,26	31,94	35,63	39,31
Ruthenium Ru	4,97	7,96	10,94	13,92	16,91	19,89	22,87	25,86	28,84	31,82
Silicon Si	815426,5	1304682	1793938	2283194	2772450	3261706	3750962	4240218	4729474	5218730
Samarium Sm	0,09	0,14	0,20	0,25	0,30	0,35	0,41	0,46	0,51	0,57
Strontium Sr	5.197,43	8.315,89	11.434,35	14.552,81	17.671,27	20.789,73	23.908,19	27.026,65	30.145,11	33.263,57
Tantalum Ta	218,21	349,13	480,05	610,97	741,90	872,82	1.003,74	1.134,67	1.265,59	1.396,51
Terbium Tb	4,39	7,02	9,65	12,29	14,92	17,55	20,18	22,82	25,45	28,08
Titanium Ti	50.782,68	81.252,29	111.721,9	142.191,5	172.661,1	203.130,7	233.600,3	264.069,9	294.539,5	325.009,2
Tungsten W	4,1	6,55	9,01	11,47	13,92	16,38	18,84	21,29	23,75	26,21
Vanadium V	0,009	0,01	0,02	0,03	0,03	0,04	0,04	0,05	0,05	0,06
Yttrium Y	3.907,51	6.252,01	8.596,52	10.941,02	13.285,53	15.630,03	17.974,53	20.319,04	22.663,54	25.008,05
Natural Rubber	3,51	5,62	7,72	9,83	11,93	14,04	16,15	18,25	20,36	22,46

Below Figure G.10 – G.14 show the graphical results of the demand development of CRMs under a fast rollout scenario until 2030.

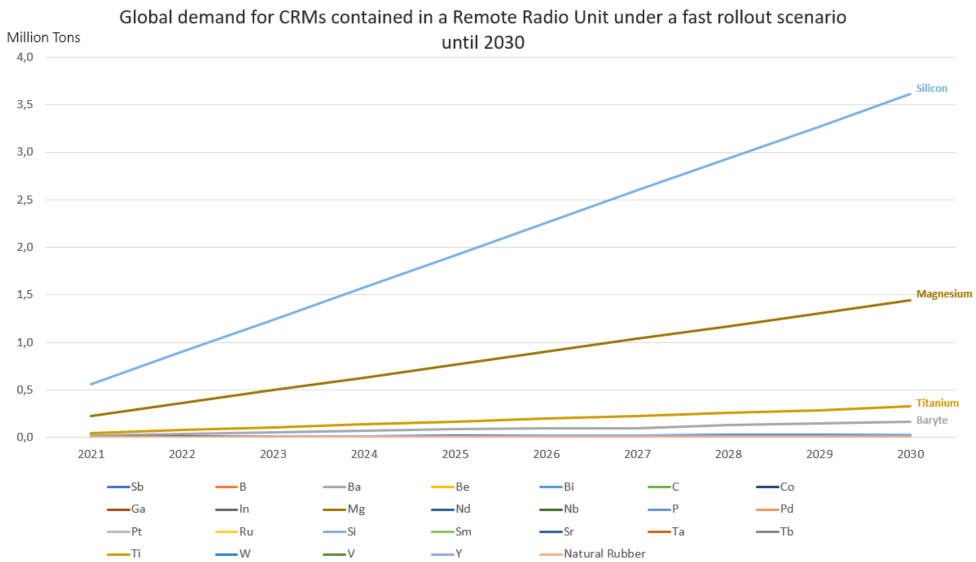


Figure G.10: Demand development of CRMs contained in a Remote Radio Unit under a fast rollout scenario until 2030.

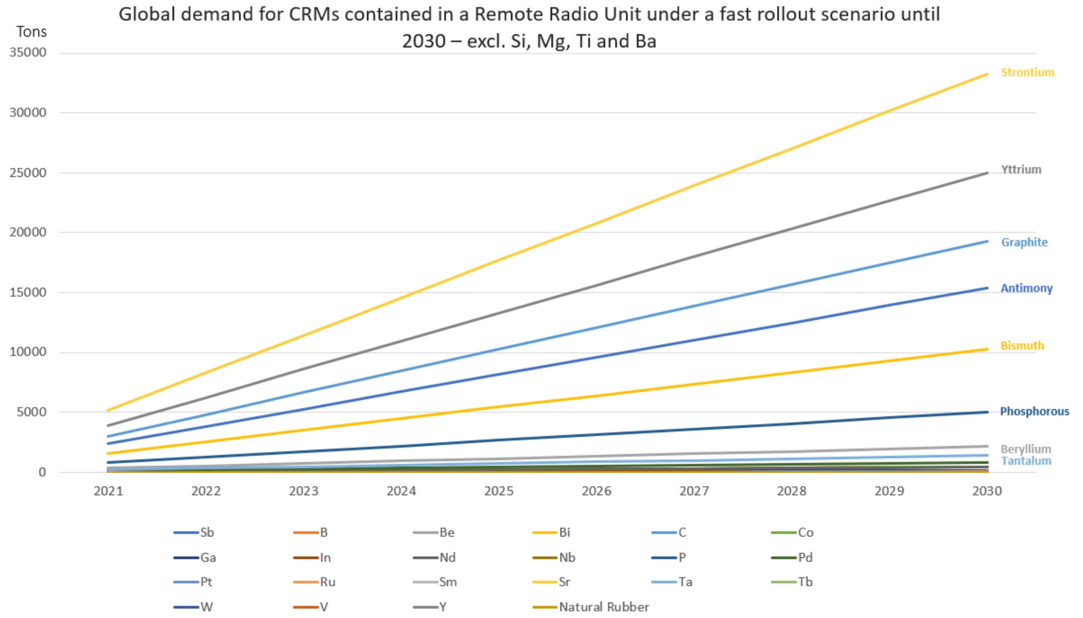


Figure G.11: Demand development of CRMs contained in a Remote Radio Unit under a fast rollout scenario until 2030 – Excluding Si, Mg, Ti and Ba.

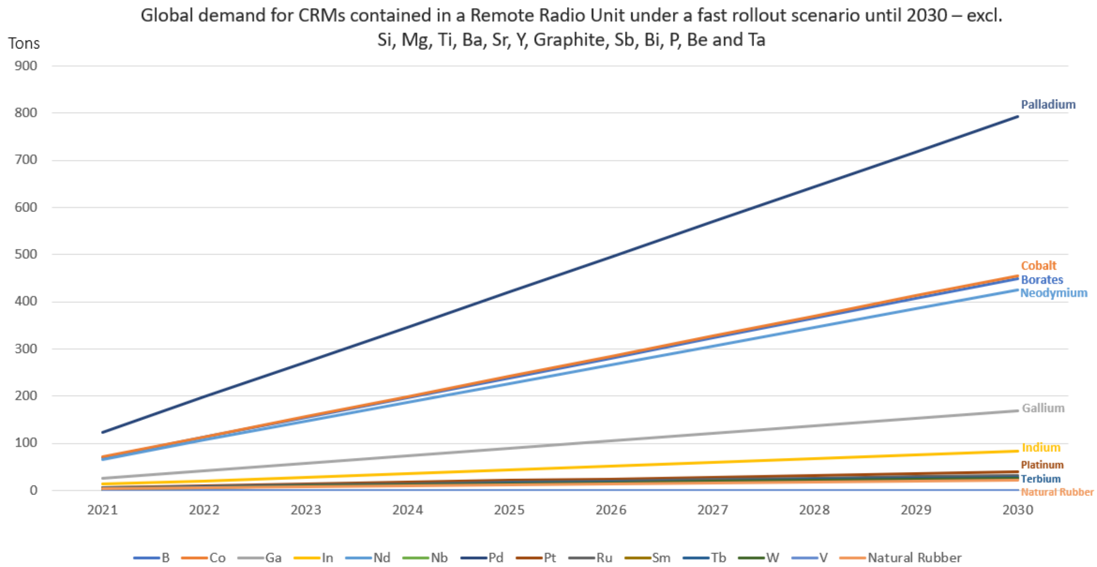


Figure G.12: Demand development of CRMs contained in a Remote Radio Unit under a fast rollout scenario until 2030 – Excluding Si, Mg, Ti, Ba, Sr, Y, Graphite, Sb, Bi, P, Be and Ta.

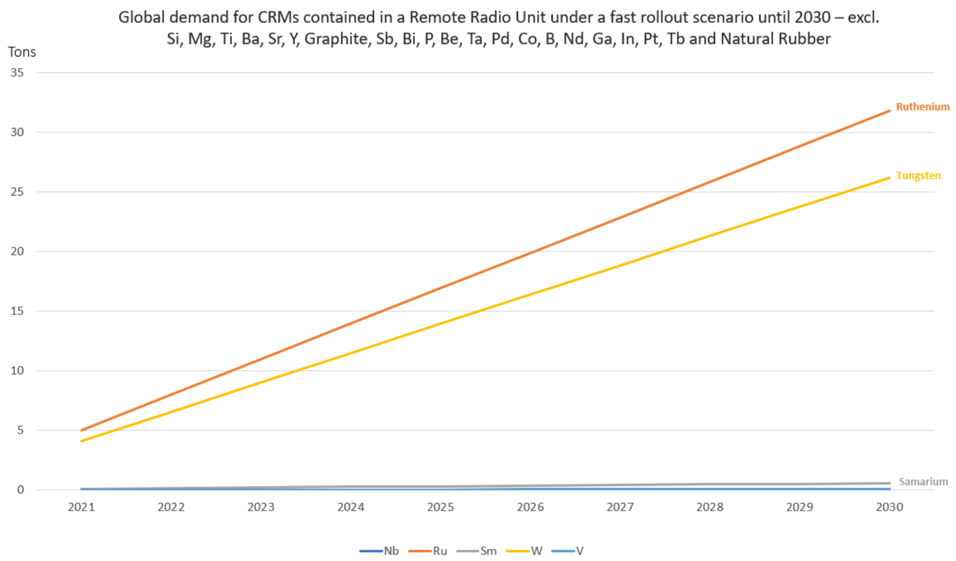


Figure G.13: Demand development of CRMs contained in a Remote Radio Unit under a fast rollout scenario until 2030 – Excluding Si, Mg, Ti, Ba, Sr, Y, Graphite, Sb, Bi, P, Be, Ta, Pd, Co, B, Nd, Ga, In, Pt, Tb and Natural Rubber.

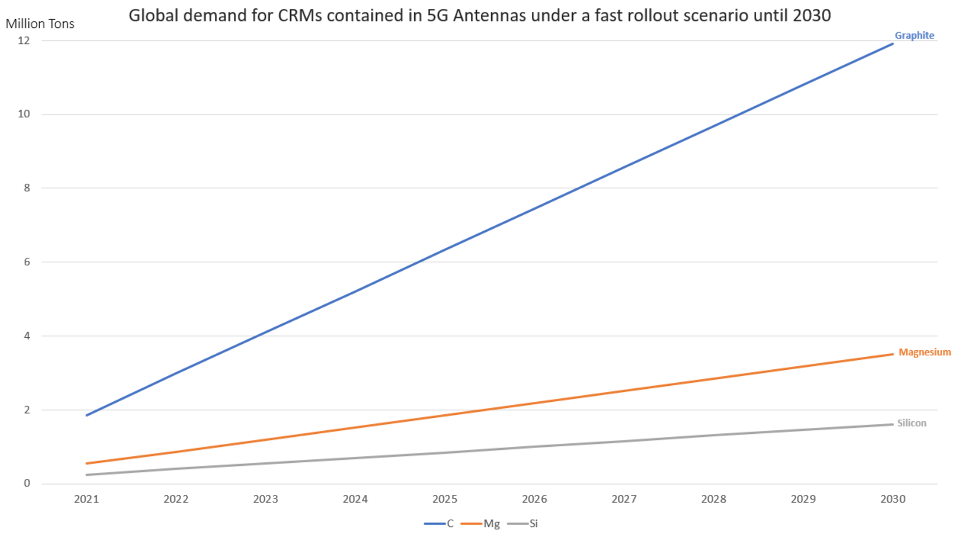


Figure G.14: Demand development of CRMs contained in an Antenna under a fast rollout scenario until 2030.

This results in the following demand developments as shown in Figure G.15 – G.18.

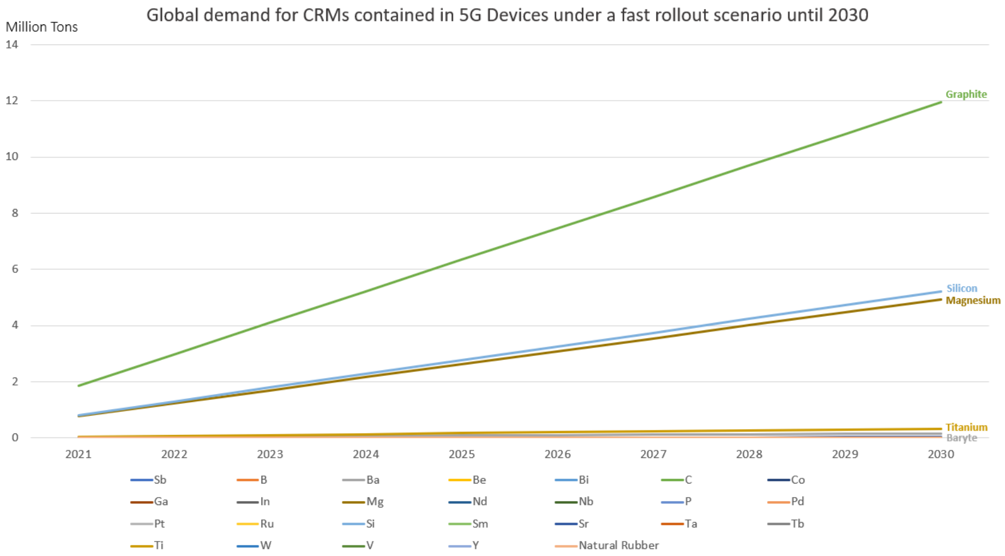


Figure G.15: Demand development of CRMs contained in 5G Devices under a fast rollout scenario until 2030.

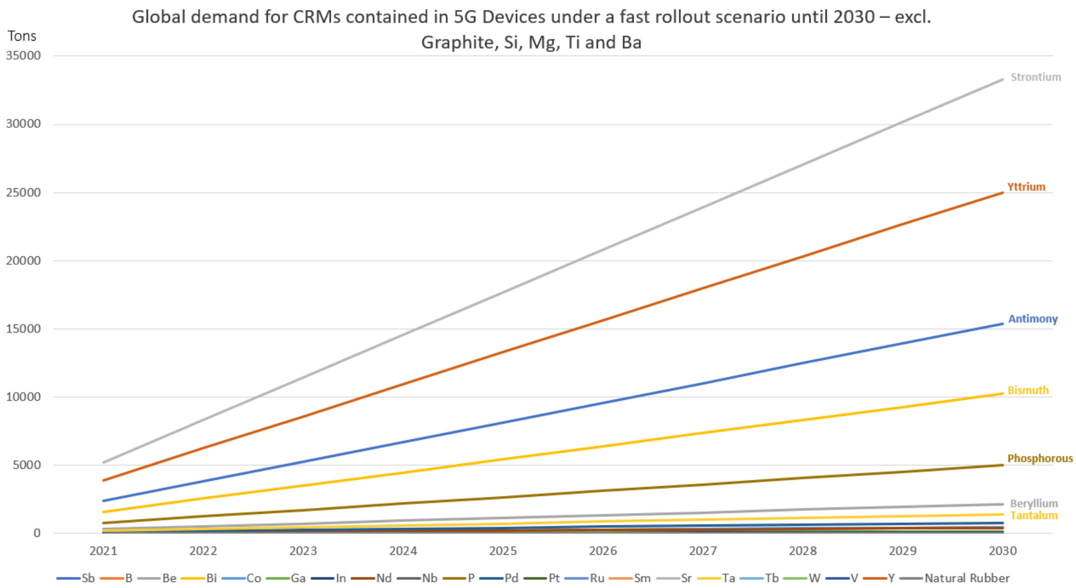


Figure G.16: Demand development of CRMs contained in 5G Devices under a fast rollout scenario until 2030 – Excluding Graphite, Si, Mg, Ti and B.

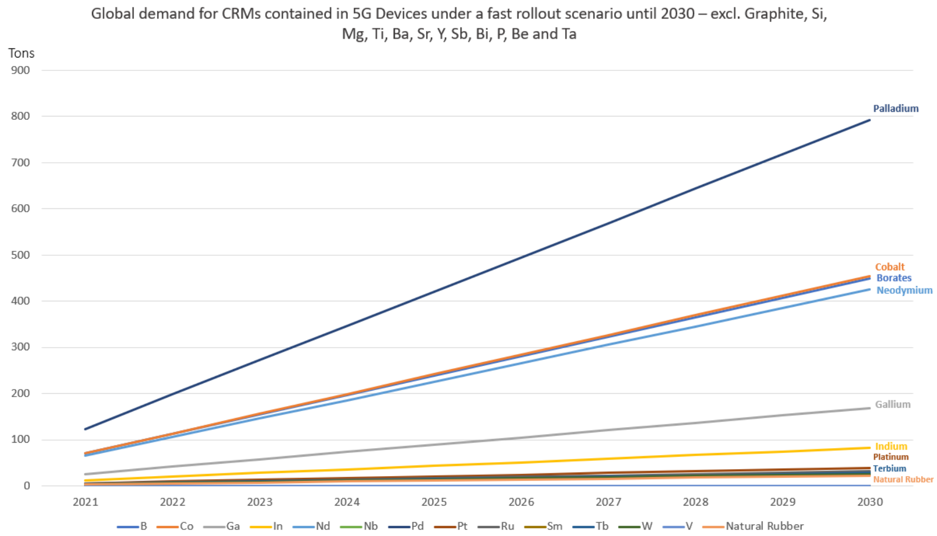


Figure G.17: Demand development of CRMs contained in 5G Devices under a fast rollout scenario until 2030 – Excluding Graphite, Si, Mg, Ti, Ba, Sr, Y, Sb, Bi, P, Be and Ta.

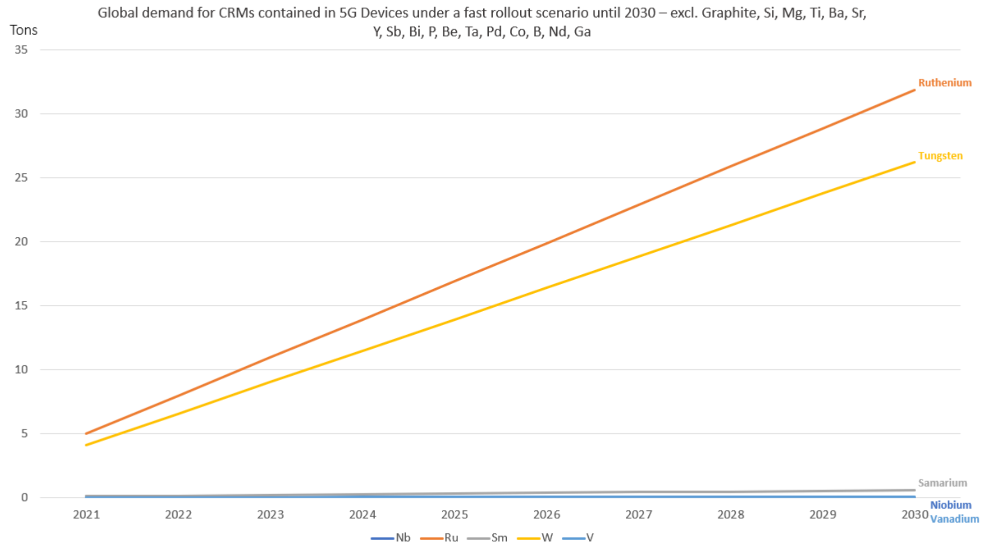


Figure G.18: Demand development of CRMs contained in 5G Devices under Scenario 2 until 2030 – Excluding Graphite, Si, Mg, Ti, Ba, Sr, Y, Sb, Bi, P, Be, Ta, Pd, Co, B, Nd, Ga, In, Pt, Tb and Natural Rubber.

Full rollout scenario of 5G Technologies

The following calculations were conducted.

$$Square\ km\ covered\ with\ 5G\ globally = 19.500.000\ km^2\ x\ 100\% = 19.500.000\ km^2$$

In order to serve an area of 19.500.000 km^2, the following amount of base stations will be needed.

$$Amount\ of\ 5G\ base\ stations = 19.500.000\ km^2 * 50 \frac{Base\ stations}{km^2}$$
$$= 975\ million\ 5G\ base\ stations$$

These amount of base stations would require the following amount of RRUs and antennas.

$$Amount\ of\ RRUs\ globally\ = \ 975\ million\ \ x\ 2\ RRUs = 1.950\ million\ RRUs$$

$$Amount\ of\ antennas\ globally\ = 58{,}50\ million\ x\ 3\ antennas = 2.925\ million\ antennas$$

Appendix H1: Photonics – Critical Raw Material Weights in Equipment

Calculation of CRM weights contained in Photonic Transceivers together with Expert C for Photonic Devices (2021)

For the calculation of critical raw material contents, the density of different raw materials need to be used. This is summarized in the below Table H1.1.

Table H1.1: Density of selected raw materials.

Element	Density	Element	Density
ZrO2	$5{,}68\ \frac{g}{cm^3}$	PbTe	$8{,}16\frac{g}{cm^3}$
Cu	$8940\ \frac{g}{cm^3}$	AuSn	$24{,}18\ \frac{g}{cm^3}$
Au	$19{,}3\ \frac{g}{cm^3}$	In	$7{,}31\ \frac{g}{cm^3}$
AlN	$3{,}26\frac{g}{cm^3}$	Bi	$9{,}79\ \frac{g}{cm^3}$
Au	$10{,}49\frac{g}{cm^3}$	Si	$2{,}3\frac{g}{cm^3}$
Bi_2Te_3	$7{,}79\frac{g}{cm^3}$		

Lower level component: Housing

Elements contained in the alloy ZAMAK 3					
Zi	Al	Cu	Mg	Pb	Cd
95.14	3.96	6.84	0.041	0.0023	0.0001
Ti	Ni	Indium	Thalium	Fe	—
0.0001	0.0006	0.0001	0.0001	0.006	—

ZAMAK: Zinc, aluminum, magnesium and copper

The housing represents 90% of the total 50g transceiver.

0,90 * 50g = 45g

Mg: $0{,}041\%\ \times 45g = 0{,}0063g$

Zn: $95{,}14\%\ \times 45g = 42{,}813g$

Al: $3{,}96\%\ \times 45g = 1{,}782g$

Cu: $6{,}84\%\ \times 45g = 3{,}078g$

Pb: $0{,}0023\%\ \times 45g = 0{,}001035g$

Cd: $0{,}0001\%\ \times 45g = 0{,}000045g$

Lower level component: Ferrule

ZrO2: $1{,}25mm\ \times 10mm\ \times 0{,}25mm = 3{,}9m_3\ \times 2 = 0{,}0078cm^3\ \times 5{,}68\ \frac{g}{cm^3} = 0{,}0443g$

Lower level component: Connector Lanes

Cu: $13mm^3 \times 8940 \frac{g}{cm^3} = 1{,}1622 \times 10^{-4}kg = 1{,}1622 \times 10^{-7}g$

Gold (Au) represents 5% the mass of copper in connector lanes.

Au: $5\% \times 1{,}1622 \times 10^{-7}g = 5{,}811 \times 10^{-9}g$

Lower level component: Wires

20 wires per transceiver.

$$V = \pi \times r^2 \times h$$

Au: $V = \pi \times (\frac{0{,}00085cm^2}{2})^2 \times 0{,}3cm = 1{,}7024 \times 10^{-7}cm \times 20 = 3{,}405 \times 10^{-6}cm^3 \times 19{,}3 \frac{g}{cm^3} = 6{,}5774 \times 10^{-5}g$

Lower level component: Ceramics

There are always two layers of ceramics.

AlN: $500\mu m \times 4mm^2 \times 2 \times 3{,}26 \frac{g}{cm^3} = 0{,}05cm \times 0{,}04cm^2 \times 2 \times 3{,}26 \frac{g}{cm^3} = 0{,}013g$

Lower level component: Epoxy

Au: $0{,}002cm \times 0{,}04cm^2 \times 2 \times 10{,}49 \frac{g}{cm^3} = 1{,}6784 \times 10^{-3}g$

Lower level component: Thermal Stabilization

Total: $0{,}05cm \times 50\% \times 0{,}04cm^2 = 1 \times 10^{-3}cm^3$

Bi_2Te_3: $1 \times 10^{-3}cm^3 \times 7{,}79 \frac{g}{cm^3} = 7{,}79 \times 10^{-3}g$

PbTe: $1 \times 10^{-3}cm^3 \times 8{,}16 \frac{g}{cm^3} = 8{,}16 \times 10^{-3}g$

Lower level component: Solders

The AuSn alloy consists of 80% Au and 20% Sn. 20 wires require solders.

AuSn: $V = \pi \times (\frac{0{,}0025cm^2}{2})^2 \times 0{,}0007cm = 3{,}4361 \times 10^{-9}cm^3 \times 24{,}18 \frac{g}{cm^3} = 4{,}8723 \times 10^{-8}g$

Au: $3{,}8978 \times 10^{-8}g$

Sn: $9{,}7446 \times 10^{-9}g$

In: $V = \pi \times (\frac{0{,}00085cm^2}{2})^2 \times 0{,}3cm = 6{,}8094 \times 10^{-7}cm^3 \times 20 \times 7{,}31 \frac{g}{cm^3} = 9{,}95534 \times 10^{-5}g$

Bi: $= 6{,}8094 \times 10^{-7}cm^3 \times 20 \times 9{,}79 \frac{g}{cm^3} = 1{,}3333 \times 10^{-4}g$

Lower level component: Electronics

Si: $0{,}4cm \times 0{,}3cm \times 0{,}05cm \times 2{,}3 \frac{g}{cm^3} \times 2 = 0{,}0276g$

Table H1.2: Aggregated Weights of a Photonics Transceiver.

Lower Level Component	Weight per CRM	
… of Transceiver	**CRM**	**Weight (g)**
Thermal Stabilizer	Bismuth Bi	0,004028
PIC	Gallium Ga	0,0001
PIC	Germanium Ge	0,000010
PIC	Indium In	0,03135
Housing	Magnesium Mg	0,0063
PIC	Palladium Pd	0,00001
PIC	Phosphorous P	0,03125
PIC	Platinum Pt	0,00004
Electronics	Silicon Si	0,0276
PIC	Titanium Ti	0,00001
	Total Weight CRMs	0,101

The gathered data on the Photonics Amplifier can be found in below Table H1.3.

Table H1.3: Aggregated Weights of a Photonics Amplifier.

Lower Level Component	Weight per CRM (g)	
… of Amplifier	**CRM**	**Weight (g)**
Generally	Bismuth Bi	0,63
	Erbium Er	1,78
	Germanium Ge	4,5
	Praseodymium Pr	0,33
	Silicon Si	495
	Thulium Tm	1,94

Appendix H2: Photonics – Critical Raw Material Demand Development

Slow rollout of Photonics until 2030

Calculated device amounts were multiplied with CRM weights and can be found in the below tables.

Table H2.1: CRM weight development of Photonics Transceivers until 2030 under a slow rollout scenario.

Weight per CRM		Development over time (t)									
CRM	**Weight (g)**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Bismuth Bi	0,004	0,76	0,83	0,9	0,98	1,07	1,16	1,27	1,38	1,5	1,64
Gallium Ga	0,0001	0,02	0,02	0,02	0,02	0,03	0,03	0,03	0,03	0,04	0,04
Germanium Ge	0,00001	0,002	0,002	0,002	0,002	0,003	0,003	0,003	0,003	0,004	0,004
Indium In	0,031	5,91	6,44	7,01	7,64	8,32	9,06	9,86	10,74	11,69	12,74
Magnesium Mg	0,0063	1,19	1,29	1,41	1,53	1,67	1,82	1,98	2,16	2,35	2,56
Palladium Pd	0,00001	0,002	0,002	0,002	0,002	0,003	0,003	0,003	0,003	0,004	0,004
Phosphorous P	0,0313	5,89	6,42	6,99	7,61	8,29	9,03	9,83	10,71	11,66	12,7
Platinum Pt	0,00004	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,02	0,02
Silicon Si	0,0276	5,21	5,67	6,17	6,72	7,32	7,97	8,68	9,45	10,3	11,21
Titanium Ti	0,00001	0,002	0,002	0,002	0,002	0,003	0,003	0,003	0,003	0,004	0,004

Table H2.2: CRM weight development of Photonics Amplifiers until 2030 under a slow rollout scenario.

Weight per CRM		Development over time (t)									
CRM	**Weight (g)**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Bismuth Bi	0,63	5,94	6,47	7,05	7,67	8,34	9,1	9,91	10,79	11,75	12,8
Erbium Er	1,78	16,79	18,28	19,91	21,68	23,61	25,71	28	30,49	33,2	36,12
Germanium Ge	4,50	42,44	46,21	50,32	54,8	59,68	64,99	70,78	77,08	83,94	91,41
Praseodymium Pr	0,33	3,11	3,39	3,69	4,02	4,38	4,77	5,19	5,65	6,16	6,7
Silicon Si	495,00	4.667,85	5.083,3	5.535,7	6.028,38	6.564,9	7.149,18	7.785,46	8.478,36	9.232,94	10.054,67
Thulium Tm	1,94	18,29	19,92	21,7	23,63	25,73	28,02	30,51	33,23	36,19	39,41

Table H2.3: Aggregated CRM weight for Photonic Devices until 2030 under a slow rollout scenario.

Development over time (t)										
CRM	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Bismuth Bi	6,7	7,3	7,94	8,65	9,42	10,26	11,18	12,17	13,25	14,43
Erbium Er	16,79	18,28	19,91	21,68	23,61	25,71	28	30,49	33,2	36,16
Gallium Ga	0,02	0,02	0,02	0,02	0,03	0,03	0,03	0,03	0,04	0,04
Germanium Ge	42,44	46,21	50,33	54,81	59,68	65	70,78	77,08	83,94	91,41
Indium In	5,91	6,44	7,01	7,64	8,32	9,06	9,86	10,74	11,69	12,74
Magnesium Mg	1,19	1,29	1,41	1,53	1,67	1,82	1,98	2,16	2,35	2,56
Palladium Pd	0,002	0,002	0,002	0,002	0,003	0,003	0,003	0,003	0,004	0,004
Phosphorous P	5,89	6,42	7	7,61	8,29	9,03	9,83	10,71	11,66	12,7
Platinum Pt	0,008	0,008	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,02
Praseodymium Pr	3,11	3,39	3,69	4,02	4,38	4,77	5,19	5,65	6,16	6,7
Silicon Si	4673	5.088,96	5.541,87	6.035,10	6.572,23	7.157,15	7.794,14	8.487,82	9.243,23	10.065,88
Titanium Ti	0,002	0,002	0,002	0,003	0,003	0,003	0,003	0,003	0,004	0,004
Thulium Tm	18,29	19,92	21,7	23,63	25,73	28,02	30,51	33,23	36,19	39,41

Below Figure H2.1 – H2.4 show the results of the demand development of Photonics devices under a slow rollout scenario until 2030.

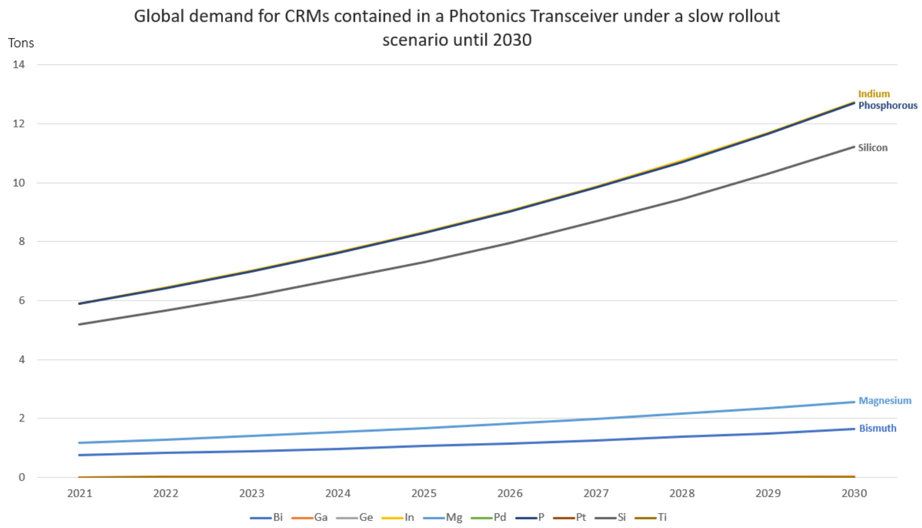


Figure H2.1: Demand development of CRMs contained in a Photonics Transceiver under a slow rollout scenario until 2030.

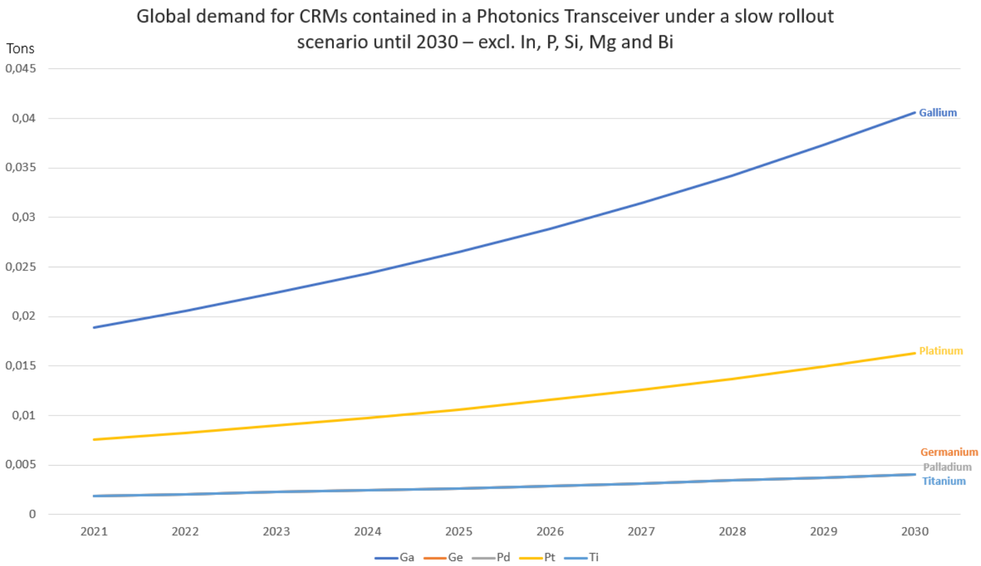


Figure H2.2: Demand development of CRMs contained in a Photonics Transceiver under a slow rollout scenario until 2030 – Excluding In, P, Si, Mg and Bi.

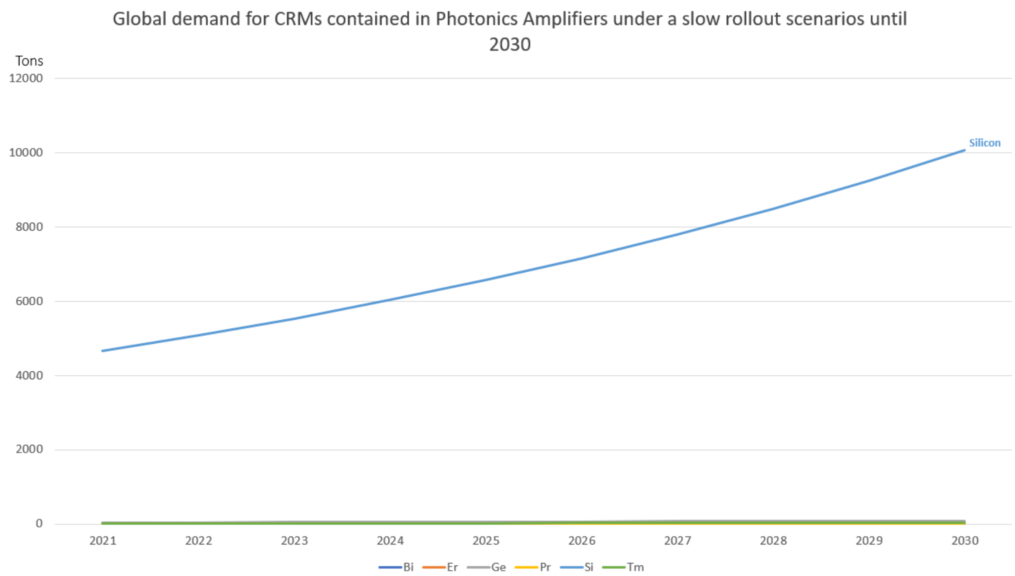


Figure H2.3: Demand development of CRMs contained in a Photonics Amplifier under a slow rollout scenario until 2030.

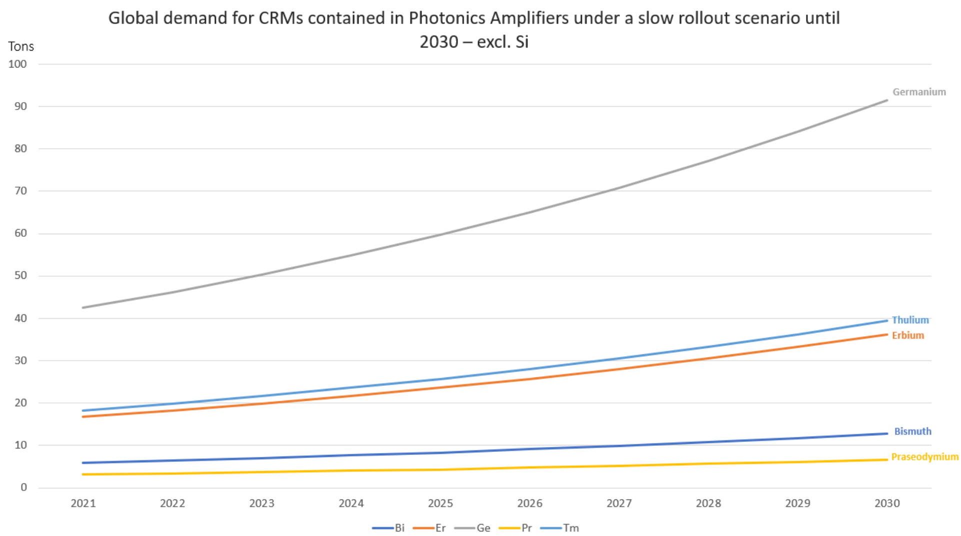


Figure H2.4: Demand development of CRMs contained in a Photonics Amplifier under a slow rollout scenario until 2030, excluding Si.

The following Figure H2.5 – H2.7 shows the demand development under the slow rollout scenario until 2030.

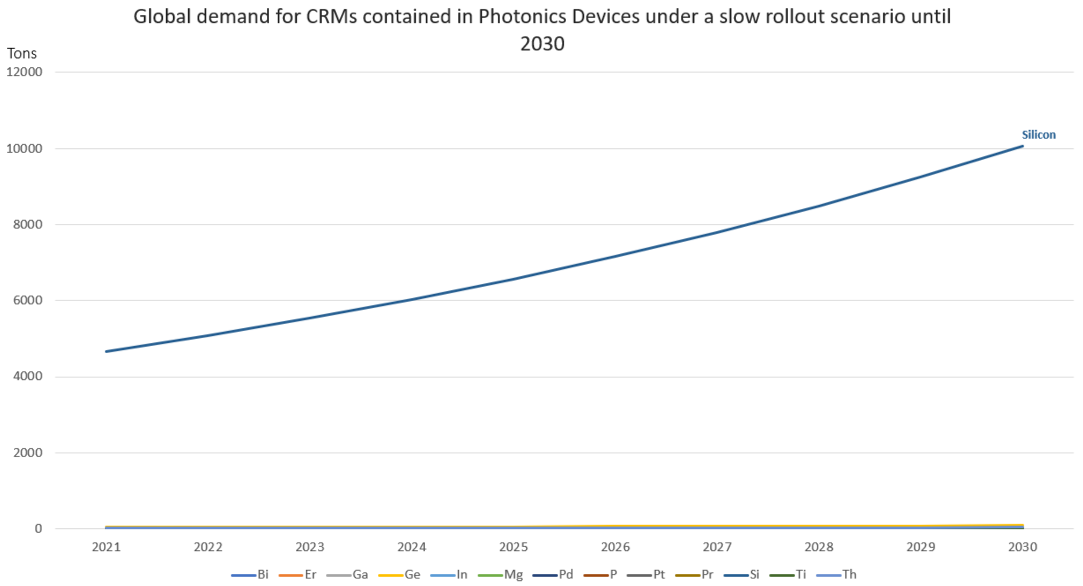


Figure H2.5: Demand development for CRMs contained in Photonics Devices under a slow rollout until 2030.

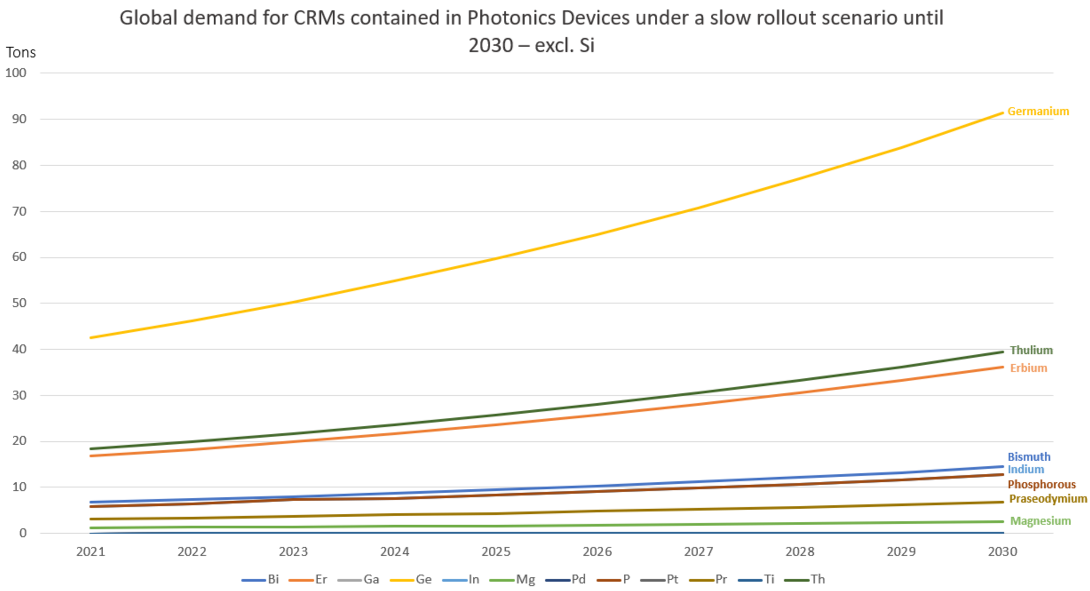


Figure H2.6: Demand development for CRMs contained in Photonics Devices under a slow rollout scenario until 2030 – Excluding Si.

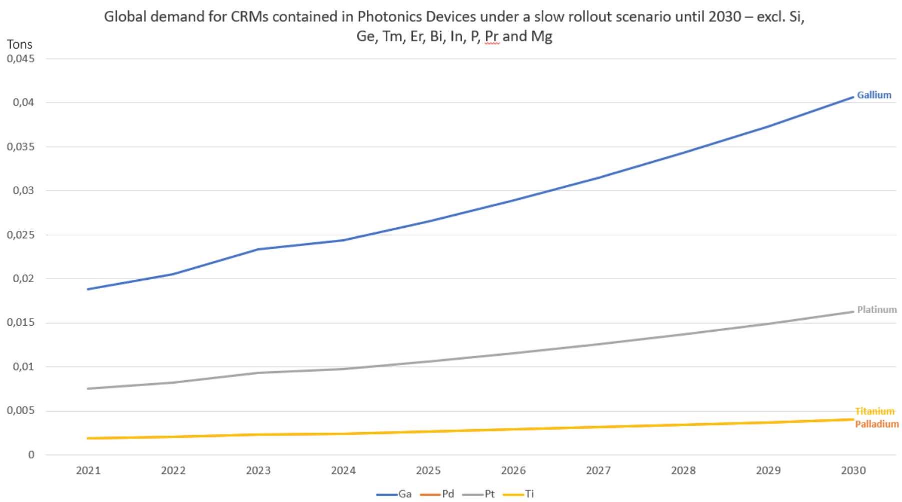


Figure H2.7: Demand development for CRMs contained in Photonics Devices under a slow rollout scenario until 2030 – Excluding Si, Ge, Tm, Er, Bi, In, P, Pr and Mg.

Fast rollout of Photonics until 2030

The second scenario was developed with device amounts gathered from Supplier B for Photonics Devices, as shown in Table H2.4.

Table H2.4: Annual transceivers shipments globally from 2016 – 2025 according to Supplier B for Photonic Devices.

	2016	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**
Transceivers shipped (in Million)	73,8	68,2	86,1	96,00	97,6	97,6	93,8	93,8	94,7	99,3

In order to estimate the growth development from 2026 – 2030, firstly the historic CAGR of the time frame 2016 – 2020 was calculated in order to then use this growth rate to scale up the amount of transceivers until 2030. This results in the following calculations.

$$CAGR_{transceiver\ development\ 2016-2025} = \left(\frac{Value\ 2025}{Value\ 2016}\right)^{\frac{1}{10}} - 1$$

$$CAGR_{transceiver\ development\ 2016-2025} = \left(\frac{99{,}3\ million}{73{,}8\ million}\right)^{\frac{1}{10}} - 1 = 0{,}03 = 3\%$$

Using a CAGR of 3% from 2026 until 2030 results in the following number for transceiver shipments as shown in Table H2.5.

Table H2.5: Transceivers shipped globally from 2025 – 2030 according to Supplier B for Photonic Devices.

	2026	**2027**	**2028**	**2029**	**2030**
Transceivers shipped (in Million)	102,28	105,35	108,51	111,76	115,12

Having those device developments captured, the following two Table H2.6 – H2.8 represent the weight numbers associated with the developments.

Table H2.6: CRM weight development of Photonics Transceivers until 2030 under a fast rollout scenario.

Weight per CRM		Development over time (t)									
CRM	**Weight (g)**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Bismuth Bi	0,004	0,76	1,14	1,51	1,89	2,3	2,71	31,33	3,57	4,02	4,48
Gallium Ga	0,0001	0,019	0,03	0,04	0,05	0,06	0,07	0,78	0,09	0,1	0,11
Germanium Ge	0,00001	0,002	0,003	0,004	0,005	0,006	0,007	0,01	0,01	0,01	0,01
Indium In	0,031	5,91	8,85	11,79	14,73	17,88	21,08	243,84	27,79	31,29	34,9
Magnesium Mg	0,0063	1,19	1,78	2,37	2,96	3,59	4,24	49	5,58	6,29	7,01
Palladium Pd	0,00001	0,002	0,003	0,004	0,005	0,006	0,007	0,08	0,01	0,01	0,011
Phosphorous P	0,0313	5,89	8,83	11,76	14,69	17,82	21,02	243,07	27,7	31,19	34,79
Platinum Pt	0,00004	0,008	0,01	0,02	0,02	0,02	0,03	0,31	0,04	0,04	0,04
Silicon Si	0,0276	5,21	7,79	10,38	12,97	15,74	18,56	214,68	24,46	27,55	30,72
Titanium Ti	0,00001	0,002	0,003	0,004	0,005	0,006	0,007	0,01	0,01	0,01	0,01

Table H2.7: CRM weight development of Photonics Amplifiers until 2030 under a fast rollout scenario.

Weight per CRM		Development over time (t)									
CRM	**Weight (g)**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Bismuth Bi	0,63	5,94	8,9	11,85	14,81	17,96	21,18	24,5	27,92	31,44	35,07
Erbium Er	1,78	16,79	25,13	33,4818	41,83	50,75	59,84	69,22	78,89	88,84	99,07
Germanium Ge	4,50	42,44	63,54	84,65	105,75	128,3	151,29	175,01	199,44	224,6	250,47
Praseodymium Pr	0,33	3,11	4,66	6,21	7,76	9,41	11,09	12,83	14,63	16,47	18,37
Silicon Si	495,00	4.667,85	6.989,4	9.310,95	11.632,5	14.112,45	16.641,9	19.250,55	21.938,4	24.705,45	27.551,7
Thulium Tm	1,94	18,29	27,39	36,49	45,59	55,31	65,22	75,45	85,98	96,83	107,98

Table H2.8: Aggregated CRM weight for Photonic Devices under a fast rollout scenario until 2030.

Development over time (t)										
CRM	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Bismuth Bi	6,70	10,03	13,37	16,7	20,26	23,89	55,83	31,49	35,46	39,55
Erbium Er	26,79	25,13	33,48	41,83	50,75	59,84	69,22	78,89	88,84	99,07
Gallium Ga	0,02	0,03	0,038	0,047	0,057	0,067	0,78	0,09	0,1	0,11
Germanium Ge	42,44	63,54	84,65	105,75	128,3	151,3	175,08	199,44	224,61	250,48
Indium In	5,91	8,85	11,79	14,73	17,88	21,08	243,85	27,79	31,29	34,9
Magnesium Mg	1,19	1,78	2,37	2,96	3,59	4,24	49	5,58	6,29	7,01
Palladium Pd	0,002	0,003	0,004	0,005	0,006	0,007	0,008	0,008	0,01	0,01
Phosphorous P	5,89	8,83	11,76	14,69	17,82	21,02	243,07	27,7	31,19	34,79
Platinum Pt	0,008	0,011	0,02	0,02	0,023	0,027	0,031	0,04	0,04	0,04
Praseodymium Pr	3,11	4,66	6,21	7,76	9,41	11,09	12,83	14,63	16,47	18,37
Silicon Si	4673	6.997,2	9.321,3	11.645,47	14.128,19	16.660,46	19.465,23	21.962,86	24.733	27.582,42
Titanium Ti	0,002	0,003	0,004	0,005	0,006	0,007	0,008	0,009	0,01	0,01
Thulium Tm	18,29	27,39	36,49	45,59	55,31	65,22	75,45	85,98	96,83	107,98

The following Figures H2.8 – H2.11 represent the developments of the amounts.

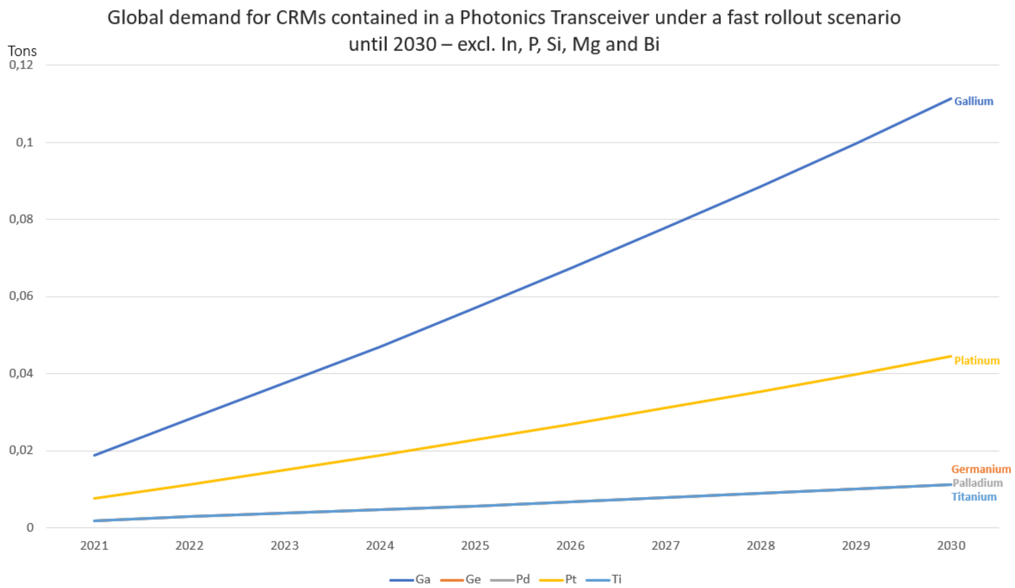


Figure H2.8: Demand development of CRMs contained in a Photonics Transceiver under a fast rollout scenario until 2030.

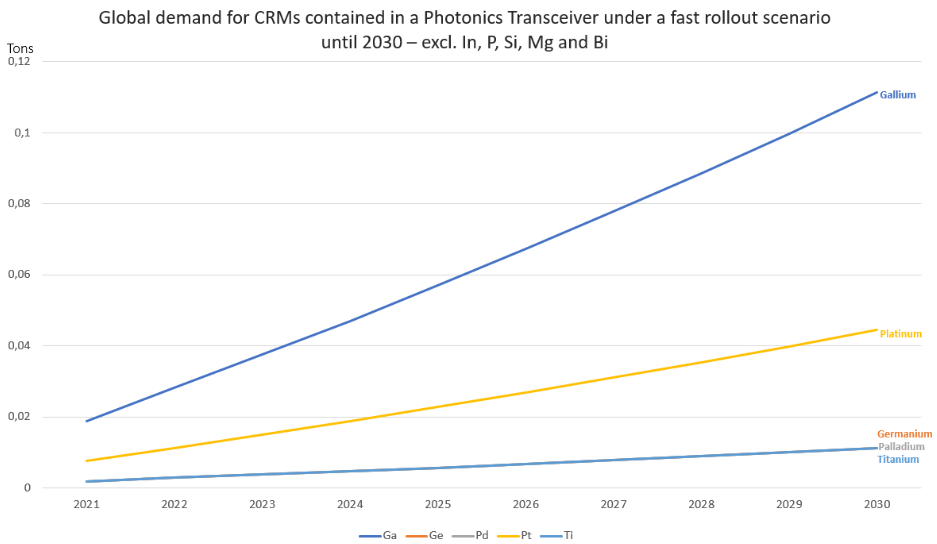


Figure H2.9: Demand development of CRMs contained in a Photonics Transceiver under a fast rollout scenario until 2030 – Excluding In, P, Si, Mg and Bi.

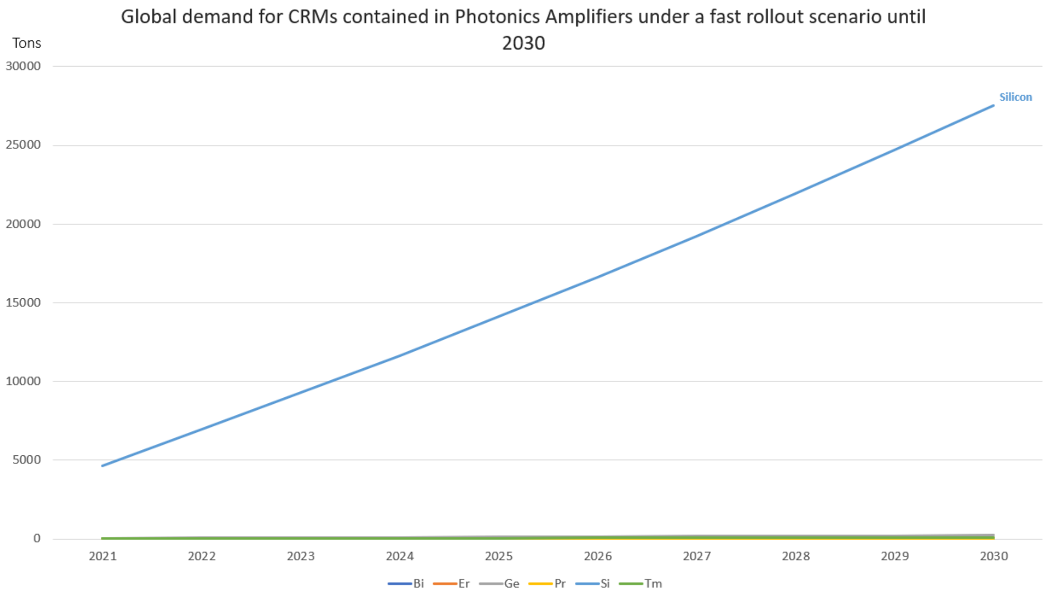


Figure H2.10: Demand development of CRMs contained in a Photonics Amplifier under a fast rollout scenario until 2030.

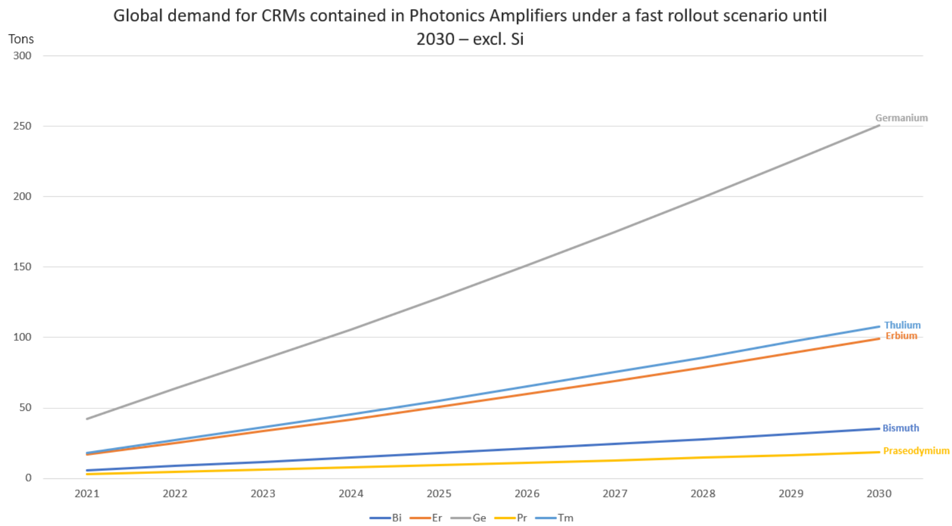


Figure H2.11: Demand development of CRMs contained in a Photonics Amplifier under a fast rollout scenario until 2030.

The following Figure H2.12 – H2.14 shows the demand development for Photonics Devices until 2030 under the fast rollout scenario.

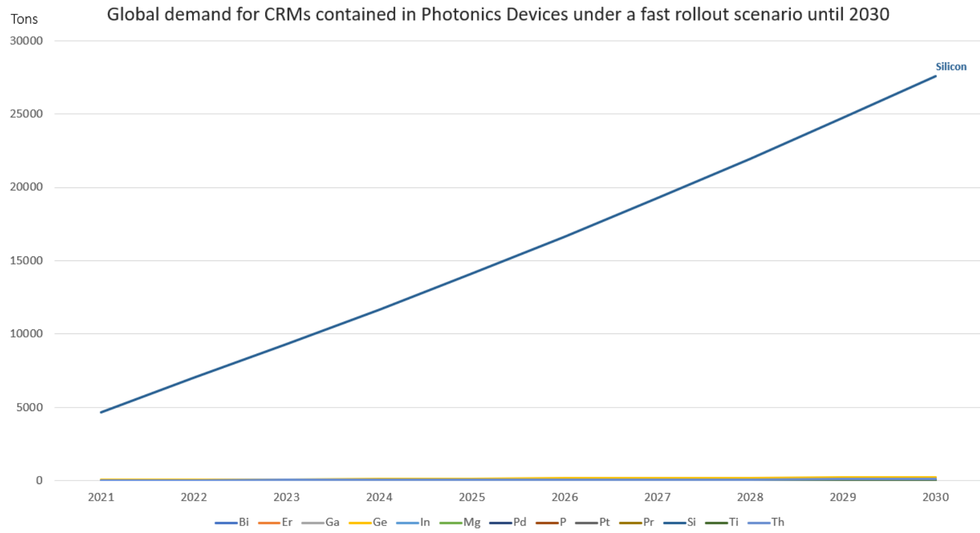


Figure H2.12: Demand development for CRMs contained in Photonics Devices under a fast rollout scenario until 2030.

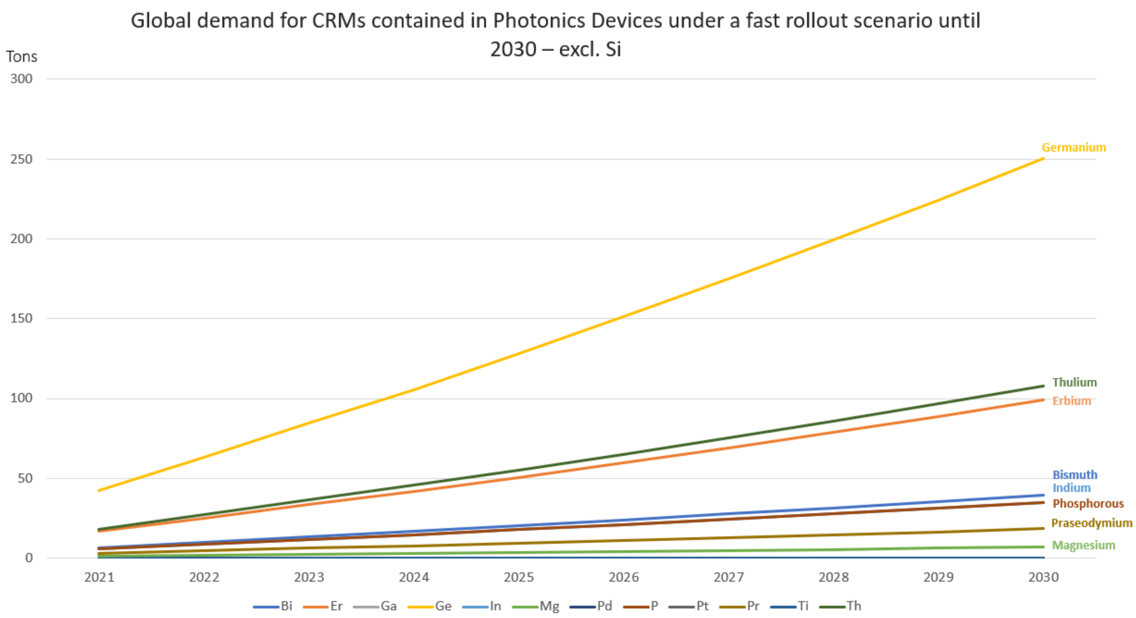


Figure H2.13: Demand development for CRMs contained in Photonics Devices under a fast rollout scenario until 2030 – Excluding Si.

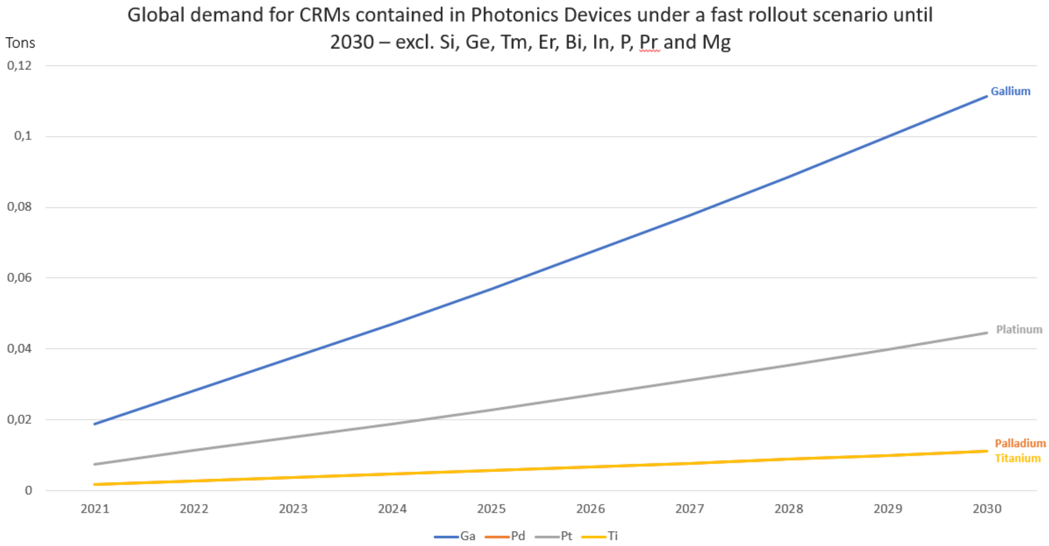


Figure H2.14: Demand development for CRMs contained in Photonics Devices under a fast rollout scenario until 2030 – Excluding Si, Ge, Tm, Er, Bi, In, P, Pr and Mg.

Full rollout scenario of Photonics

According to OECD (2020a), in 2020 around 29,18% of the OECD countries' fixed broadband was covered by fiber connections. The growth rate of fiber, which is also the fastest growing broadband technology, was 13% in the years 2018 and 2019 (OECD, 2020a). OECD does not represent the whole world, but, if looked at from the angle of the GDP, represents around 50% of the whole world (OECD, 2020b). In order to make forecasts for the whole world, the share of the global rollout was estimated by taking the share of the global GDP. This results in the following calculation.

$$Share\ of\ global\ optical\ fiber\ coverage\ (2020) = 29{,}18\% * 50\% = 0{,}1459 = 14{,}59\%$$

As part of this scenario it is assumed that in the year 2020, 183 million units of Photonic Transceivers worldwide were installed (Yole Développement, 2020), representing 14,59% of global coverage. The goal of this third scenario was to identify the amount of transceivers in use, in case the we achieve global coverage of Photonics transceivers. Thus, the following calculation was done.

$$Amount\ Transceivers_{Global\ optical\ fiber\ cable\ coverage} = 183\ million * \frac{100\%}{14{,}59\%}$$
$$= 1.254,28\ million$$

$$Amount\ Amplifiers_{Global\ optical\ fiber\ cable\ coverage} = \frac{1.254{,}28\ million}{20} = 62{,}71\ million$$

This means that with the given numbers, a hypothetical amount of 1.254,28 million transceivers and 62,71 million Photonic amplifiers would be installed globally. Furthermore, this was multiplied with the weight of CRMs contained in the devices.

Appendix I: Edge Computing – Critical Raw Material Demand Development

According to Galabov (2021), the data center market and amount of shipped servers achieved a new record in 2021. Galabov (2021) predicts, that in the weakest first quarter of 2021, around 3,1 million servers were shipped worldwide. Additionally Galabov (2021) compares this amount with the historical development of first quarters from 2016 until 2021. In order to draw conclusions on the whole shipped servers in one year, it is assumed that the same amount of servers are shipped in each quarter. Thus the amount of servers per quarter were multiplied by 4. This results in the following Table I.1 (Galabov, 2021).

Table I.1: Amount of shipped servers estimated by Galabov (2021).

In Million Units	2016	2017	2018	2019	2020	2021
Amount Servers in Q1 of each year	2,4	2,45	2,6	2,5	3,3	3,1
Calculated amount for the whole year	9,6	9,8	10,4	10	13,2	12,4

The next step was to calculate the CAGR from 2016 to 2021 in order to use this CAGR to predict future developments.

$$CAGR_{server\ development\ 2016-2021} = (\frac{Ending\ Value}{Beginning\ Value})^{\frac{1}{years}} - 1$$

$$CAGR_{server\ development\ 2016-2021} = (\frac{12{,}4\ million}{9{,}6\ million})^{\frac{1}{6}} - 1 = 0{,}044 = 4{,}4\%$$

For the further calculations, this CAGR was used to estimate the amount of servers deployed in 2024. The following Table 19 gives an overview on that.

Table I.2: Amount of shipped servers calculated until 2024 based on Galabov (2021).

In Million Units	2021	2022	2023	2024
Amount Servers in Q1 of each year	3,1	3,24	3,38	3,53
Calculated amount for the whole year	12,4	12,95	13,52	14,11

In order to make forecasts on the edge deployment, it was additionally identified which portion of servers are and will be located at the edge compared to non-edge. Leopold (2020) reports that Omdia estimated that from 2020 to 2024, the total amount of shipped servers will double, resulting in a total amount of 4,7 million servers deployed at the edge globally in 2024. This would result in the following calculations.

$$Amount\ of\ servers\ shipped\ in\ 2020 = \frac{4{,}7\ million}{2} = 2{,}35\ million\ servers$$

$$CAGR_{server\ development\ at\ the\ edge\ 2020-2024} = (\frac{4{,}7\ million}{2{,}35\ million})^{\frac{1}{5}} - 1 = 0{,}15 = 15\%$$

This results in the following number of Edge Computing servers in 2021, which will also be taken as a starting base for the scenarios.

$$Amount\ Edge\ Computing\ Servers\ in\ 2021 = 2{,}35\ million * 1{,}15 = 2{,}7\ million$$

Scenario 1: Slow rollout of Edge Computing until 2030

Below Table I.3 shows the raw data of the demand development of an Edge Computing Server under a slow rollout scenario until 2030.

Table I.3: CRM weights of an Edge Computing Server under a slow rollout scenario until 2030.

Development of amount materials until 2030 [tons]										
CRM	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Antimony Sb	11,77	12,73	13,76	14,88	16,09	17,4	18,82	20,35	22	23,79
Borates B	1.667,36	1.802,91	1.949,49	2.107,98	2.279,36	2.464,68	2.665,05	2.881,72	3.116,01	3.369,34
Baryte Ba	1.562,41	1.689,43	1.826,78	1.975,3	2.135,89	2.309,54	2.497,31	2.700,34	2.919,88	3.157,26
Cobalt Co	4.152,14	4.489,71	4.854,72	5.249,41	5.676,19	6.137,66	6.636,66	7.176,22	7.759,64	8.390,5
Dysprosium Dy	4.565,7	4.936,89	5.338,26	5.772,26	6.241,55	6.748,98	7.297,68	7.890,98	8.532,51	9.226,21
Erbium Er	0	0	0	0	0	0	0	0	0	0
Gallium Ga	21,6	23,36	25,25	27,31	29,53	31,93	34,52	37,33	40,37	43,65
Germanium Ge	0,1	0,11	0,12	0,13	0,14	0,15	0,16	0,17	0,19	0,2
Lithium Li	2.592	2.802,73	3.030,59	3.276,98	3543,4	3.831,48	4.142,974	4.479,8	4.844,01	5.237,82
Magnesium Mg	607,5	656,89	710,29	768,04	830,48	898	971,01	1.049,95	1.135,31	1.227,61
Neodymium Nd	35.383,5	38.260,18	41.370,73	44.734,17	48.371,06	52.303,63	56.555,91	61.153,91	66.125,72	71.501,74
Phosphorous P	189,89	205,33	222,02	240,07	259,59	280,7	303,52	328,19	354,87	383,73
Palladium Pd	2,62	2,83	3,06	3,31	3,58	3,87	4,19	4,53	4,89	5,29
Ruthenium Ru	2,78	3,01	3,25	3,52	3,8	4,11	4,45	4,81	5,2	5,62
Silicon SI	31.841,99	34.430,74	37.229,96	40.256,76	43.529,65	47.068,59	50.895,27	55.033,06	59.507,24	64.345,18
Tantalum Ta	733,75	793,41	857,91	927,66	1.003,08	1.084,63	1.172,81	1.268,16	1.371,26	1.482,74
Titanium Ti	1.562,41	1.689,43	1.826,78	1.975,3	2.135,89	2.309,54	2.497,31	2.700,34	2.919,88	3.157,26
Tungsten W	0,05	0,06	0,06	0,07	0,07	0,08	0,09	0,09	0,1	0,11

This development can be seen in the following Figure I.1 – I.3.

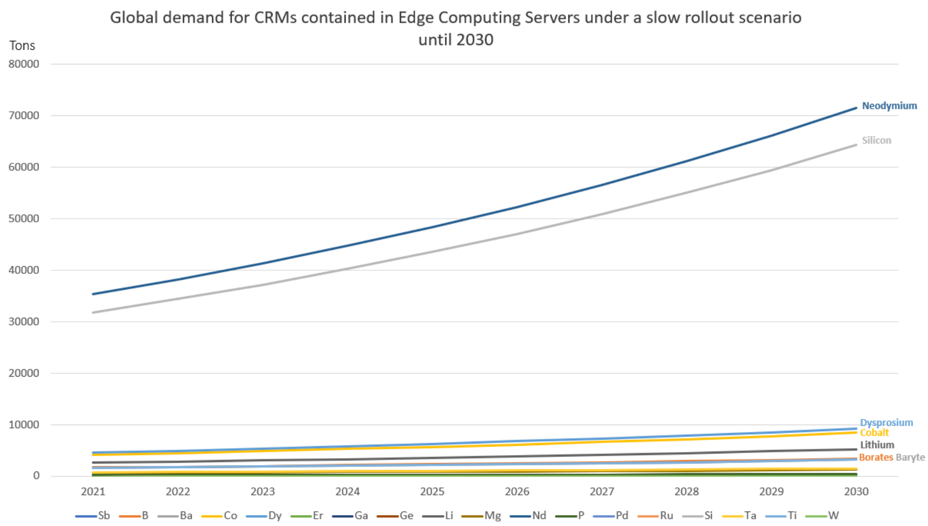


Figure I.1: Global demand development for Edge Computing Servers under a slow rollout scenario until 2030.

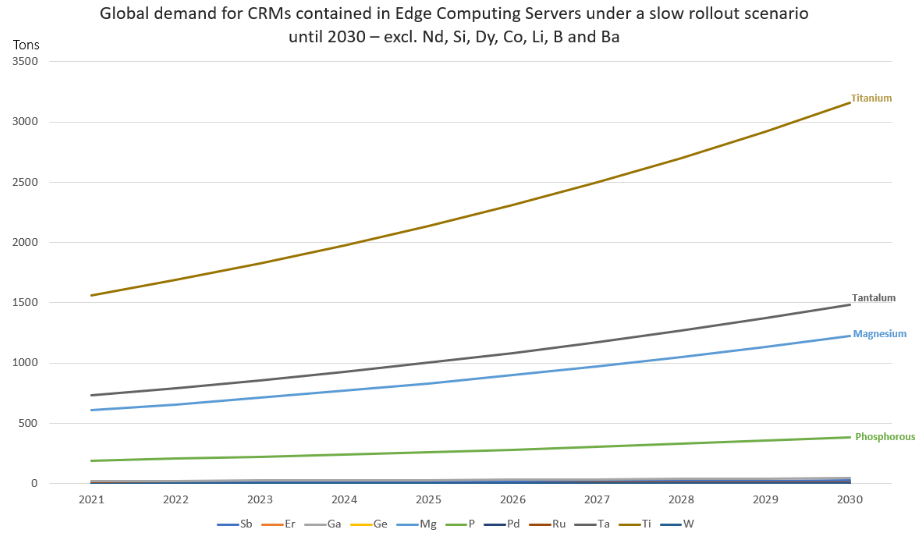


Figure I.2: Global demand development for Edge Computing Servers under a slow rollout scenario until 2030 – Excluding Nd, S, Dy, Co, Li, B and Ba.

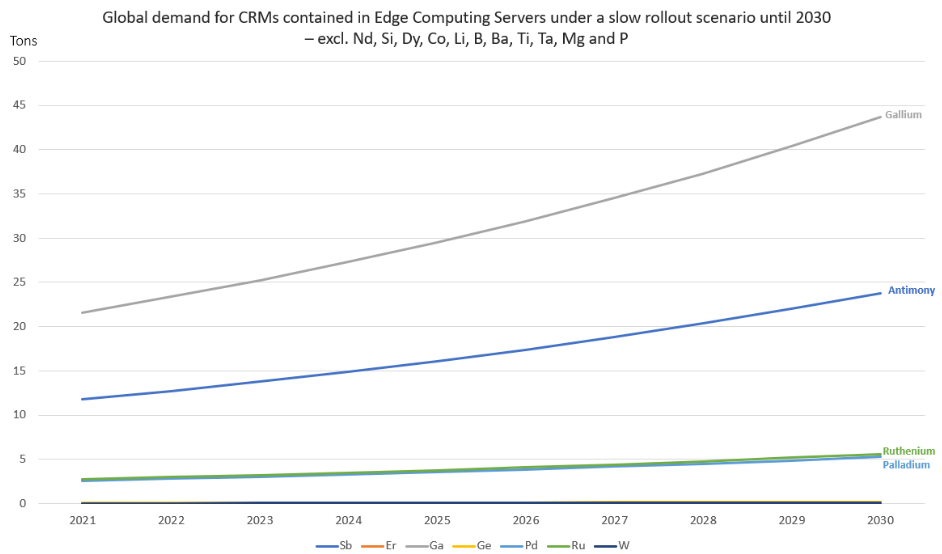


Figure I.3: Global demand development for Edge Computing Servers under a slow rollout scenario until 2030 – Excluding Nd, Si, Co, Li, B, Ba, Ti, Ta, Mg and P.

Scenario 2: Fast rollout of Edge Computing until 2030

Below Table I.4 shows the raw data of the demand development of an Edge Computing Server under a fast rollout scenario until 2030.

Table I.4: Weight development of Edge Computing Servers under a fast rollout scenario until 2030.

Development of amount materials until 2030 [tons]										
CRM	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Antimony Sb	11,77	13,54	15,57	17,9	20,59	23,68	27,23	31,31	36,02	41,41
Borates B	1.667,36	1.917,46	2.205,08	2.535,84	2.916,22	3.353,65	3.856,7	4.435,21	5.100,49	5.865,56
Baryte Ba	1.562,41	1.796,77	2.066,29	2.376,23	2.732,66	3.142,56	3.613,95	4.156,04	4.779,44	5.496,36
Cobalt Co	4.152,14	4.774,96	5.491,21	6.314,89	7.262,12	8.351,44	9.604,15	11.044,78	12.701,49	14.606,72
Dysprosium Dy	4.565,7	5.250,56	6.038,14	6.943,86	7.985,44	9.183,25	10.560,74	12.144,85	13.966,58	16.061,57
Erbium Er	0	0	0	0	0	0	0	0	0	0
Gallium Ga	21,6	24,84	28,57	32,85	37,78	43,45	49,96	57,46	66,07	75,99
Germanium Ge	0,1	0,11	0,13	0,15	0,17	0,2	0,23	0,27	0,31	0,35
Lithium Li	2.592	2.980,8	3.427,92	3.942,11	4.533,42	5.213,44	5.995,45	6.894,77	7.928,99	9.118,34

Magnesium Mg	607,5	698,63	803,42	923,93	1.062,52	1.221,9	1.405,18	1.615,96	1.858,36	2.137,11
Neodymium Nd	35.383,5	40.691,03	46.794,68	53.813,88	61.885,96	71.168,86	81.844,19	94.120,81	108.238,94	124.474,78
Phosphorous P	189,89	218,37	251,13	288,8	332,12	381,94	439,23	505,11	580,88	668,01
Palladium Pd	2,62	3,01	3,46	3,98	4,58	5,27	6,06	6,97	8,01	9,21
Ruthenium Ru	2,78	3,2	3,68	4,23	4,86	5,59	6,43	7,4	8,51	9,78
Silicon Si	31.841,99	36.618,29	42.111,03	48.427,69	55.691,84	64.045,62	73.652,46	84.700,33	97.405,38	112.016,19
Tantalum Ta	733,75	843,81	970,39	1.115,95	1.283,34	1.475,84	1.697,21	1.951,79	2.244,56	2.581,25
Titanium Ti	1.562,41	1.796,77	2.066,29	2.376,23	2.732,66	3.142,56	3.613,95	4.156,04	4.779,44	5.496,36
Tungsten W	0,05	0,06	0,07	0,08	0,09	0,11	0,12	0,14	0,17	0,19

This results in the following Figures I.4 – I.6.

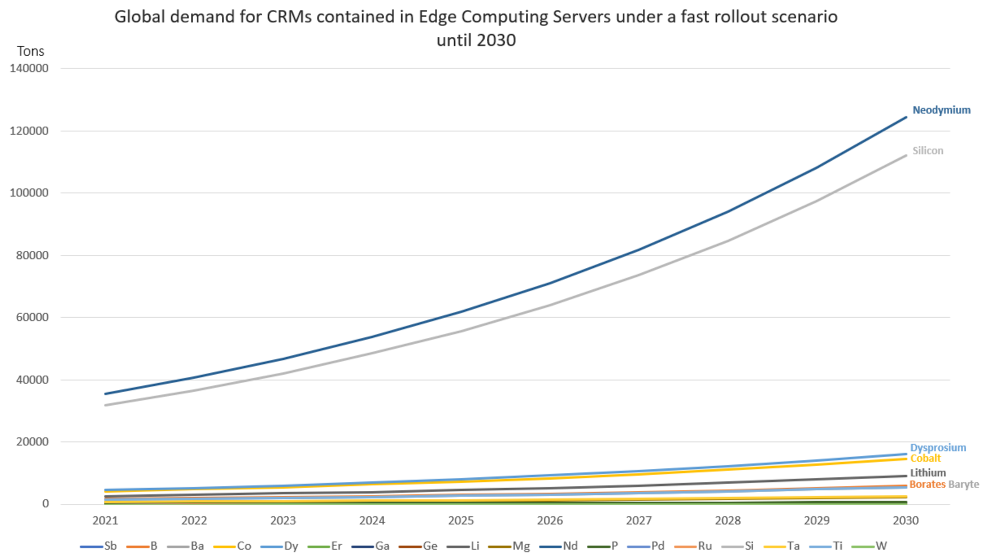


Figure I.4: Global demand development for Edge Computing Servers under a fast rollout scenario until 2030.

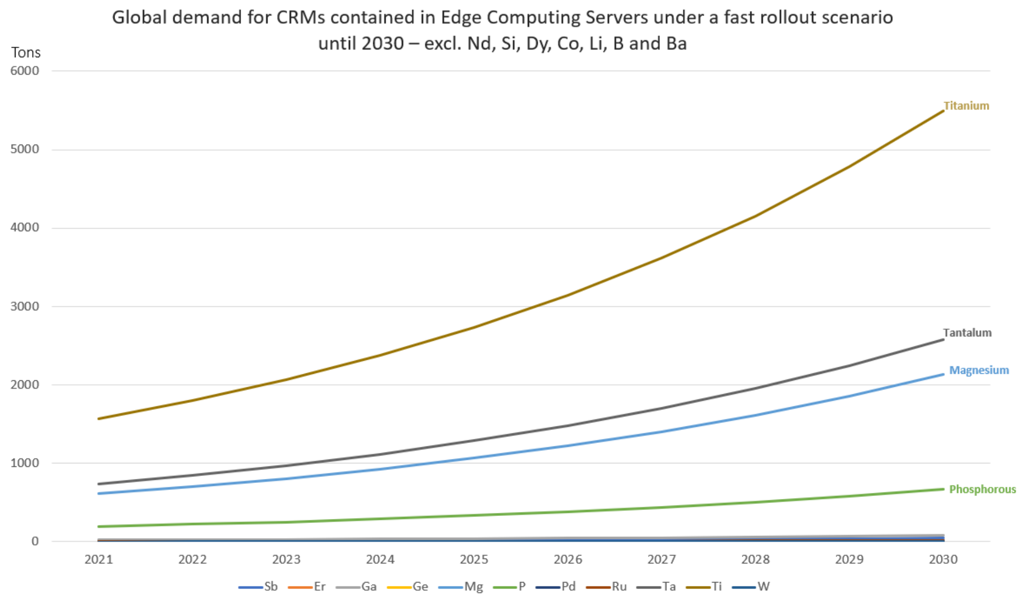


Figure I.5: Global demand development for Edge Computing Servers under a fast rollout scenario until 2030 – Excluding Nd, Si, Dy, Co, Li, B and Ba.

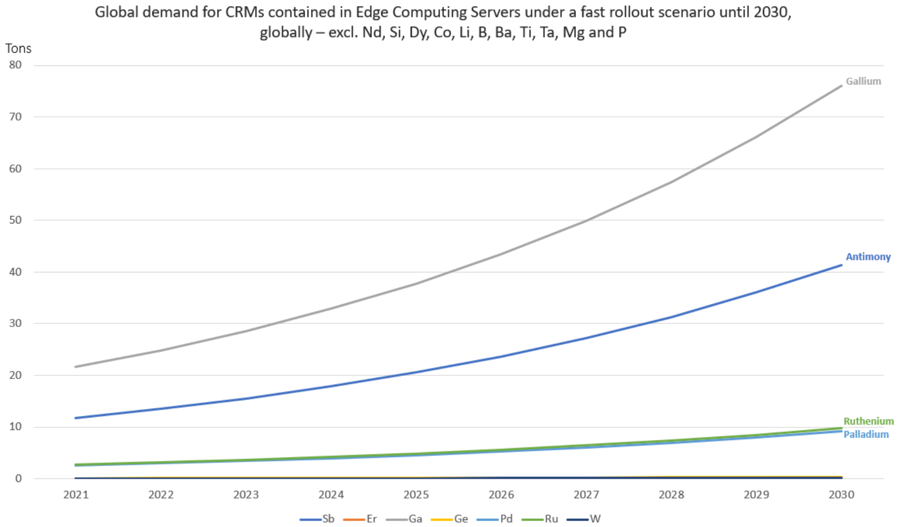


Figure I.6: Global demand development for Edge Computing Servers under a fast rollout scenario until 2030 – Excluding Nd, Si, Dy, Co, Li, B, Ba, Ti, Ta, Mg and P.

Full rollout scenario of Edge Computing Servers

In order to estimate which impact the deployment of all shipped servers at the edge would have on the resources, the amount of servers had to be identified at that point in time when the following equation holds true.

$$Servers\ shipped = Servers\ deployed\ at\ the\ edge$$

To identify this point, the growth rates of Scenario 2 $CAGR_{server\ development\ 2016-2021}$ = 4,4% and $CAGR_{server\ deployment\ at\ the\ edge\ 2020-2024}$ = 15% were taken and scaled up to that point when both numbers equal each other. Considering those growth rates, that would have potentially been in 2037. In 2037, the following number of servers would be deployed at the edge.

$$Servers\ deployed\ at\ the\ edge = 24{,}69\ millon\ units$$

These amounts of servers deployed at the edge were multiplied with the CRM weight amounts and are shown in the main text.

Appendix J1: Quantum Technologies – Critical Raw Material Weights

The below Table J1.1 – J1.3 gives an overview on the different Quantum devices, including their lower level components, where the CRMs are contained and with which weight.

Table J1.1: Aggregated Weights of a Quantum Router.

Lower Level Component	Weight per CRM	
… of Quantum Router	**CRM**	**Weight (g)**
Integrated Photonics	Gallium Ga	0,005
Integrated Photonics	Indium In	0,5
Integrated Photonics	Phosphorous P	1
Integrated Photonics, MEMS Switches	Silicon Si	21
Total Weight CRMs		22,51

Table J1.2: Aggregated Weights of a Quantum Sender.

Lower Level Component	Weight per CRM	
… of Quantum Sender	**CRM**	**Weight (g)**
Quantum Dots, Cryogenics	Beryllium Be	0,011
Quantum Dots	Graphite C	1
Cryogenics	Dysprosium Dy	0,001
Cryogenics	Erbium Er	0,001
Laser, Integrated Photonics, Quantum Dots, Cryogenics	Gallium Ga	0,14
Laser, Cryogenics	Germanium Ge	1,001
Cryogenics	Holmium Ho	0,001
Laser, Telecom Modulator, Integrated Photonics, Quantum Dots	Indium In	2,15
Telecom Modulator	Lithium Li	0,5
Telecom Modulator, Cryogenics	Niobium Nb	0,6
Laser, Telecom Modulator, Integrated Photonics, Quantum Dots, Cryogenics	Phosphorous P	2,66
Cryogenics	Praseodymium Pr	0,001
Laser, Integrated Photonics, Quantum Dots, Cryogenics	Silicon SI	23
Cryogenics	Tungsten W	0,1
Cryogenics	Natural Rubber	100
Total Weight CRMs		131,17

Table J1.3: Aggregated Weights of a Quantum Receiver.

Lower Level Component	Weight per CRM	
… of Quantum Receiver	**CRM**	**Weight (g)**
Cryogenics	Beryllium Be	0,001
Cryogenics	Dysprosium Dy	0,001
Cryogenics	Erbium Er	0,001
Quantum Detector, Integrated Photonics, Cryogenics	Gallium Ga	0,11
Cryogenics	Germanium Ge	0,001
Cryogenics	Holmium Ho	0,001
Telecom Modulator, Quantum Detector, Integrated Photonics	Indium In	1,1
Telecom Modulator	Lithium Li	0,5
Telecom Modulator, Quantum Detector, Cryogenics	Niobium Nb	0,75
Telecom Modulator, Integrated Photonics, Cryogenics	Phosphorous P	1,51
Cryogenics	Praseodymium Pr	0,001
Quantum Detector, Integrated Photonics, Cryogenics	Silicon Si	22
Quantum Detector	Titanium Ti	0,01
Quantum Detector, Cryogenics	Tungsten W	0,2
Cryogenics	Natural Rubber	100
Total Weight CRMs		126,18

Appendix J2: Quantum Technologies – Critical Raw Materials Demand Development

Scenario 1: Slow rollout of Quantum Technologies until 2050

Below Table J2.1 – J2.3 show the raw data of the CRM demand development until 2050.

Table J2.1: Aggregated Weights of a Quantum Router under a slow rollout scenario until 2050.

Weight per CRM		Development over time (t)						
CRM	**Weight (g)**	**2021**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Gallium Ga	0,005	0	0	0	0	0	0	0
Indium In	0,5	0	0	0	0,001	0,001	0,002	0,005
Phosphorous P	1	0	0	0,001	0,001	0,002	0,005	0,01
Silicon Si	21	0	0,007	0,01	0,03	0,05	0,11	0,22

Table J2.2: Aggregated Weights of a Quantum Sender under a slow rollout scenario until 2050.

Weight per CRM		Development over time (t)						
CRM	**Weight (g)**	**2021**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Beryllium Be	0,011	0	0	0	0	0	0	0
Graphite C	1	0	0,001	0,001	0,002	0,005	0,01	0,02
Dysprosium Dy	0,001	0	0	0	0	0	0	0
Erbium Er	0,001	0	0	0	0	0	0	0
Gallium Ga	0,14	0	0	0	0	0,001	0,001	0,002
Germanium Ge	1,001	0	0,001	0,001	0,002	0,005	0,01	0,02
Holmium Ho	0,001	0	0	0	0	0	0	0
Indium In	2,15	0,001	0,001	0,003	0,005	0,01	0,02	0,04
Lithium Li	0,5	0	0	0,001	0,001	0,002	0,005	0,01
Niobium Nb	0,6	0	0	0,001	0,001	0,003	0,006	0,01
Phosphorous P	2,66	0,001	0,002	0,003	0,006	0,01	0,03	0,05
Praseodymium Pr	0,001	0	0	0	0	0	0	0
Silicon Si	23	0,007	0,01	0,03	0,06	0,11	0,22	0,44
Tungsten W	0,1	0	0	0	0	0	0,001	0,002
Natural Rubber	100	0,03	0,06	0,12	0,24	0,48	0,96	1,92

Table J2.3: Aggregated Weights of a Quantum Receiver under a slow rollout scenario until 2050.

Weight per CRM		Development over time (t)						
CRM	**Weight (g)**	**2021**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Beryllium Be	0,001	0	0	0	0	0	0	0
Dysprosium Dy	0,001	0	0	0	0	0	0	0
Erbium Er	0,001	0	0	0	0	0	0	0
Gallium Ga	0,11	0	0	0	0	0,001	0,001	0,002
Germanium Ge	0,001	0	0	0	0	0	0	0
Holmium Ho	0,001	0	0	0	0	0	0	0
Indium In	1,1	0	0,001	0,001	0,003	0,005	0,01	0,02
Lithium Li	0,5	0	0	0,001	0,001	0,002	0,005	0,01
Niobium Nb	0,75	0	0	0,001	0,002	0,004	0,007	0,01
Phosphorous P	1,51	0	0,001	0,002	0,004	0,007	0,01	0,03
Praseodymium Pr	0,001	0	0	0	0	0	0	0
Silicon Si	22	0,007	0,01	0,03	0,05	0,11	0,21	0,42
Titanium Ti	0,01	0	0	0	0	0	0	0
Tungsten W	0,2	0	0	0	0	0,001	0,002	0,004
Natural Rubber	100	0,03	0,06	0,12	0,24	0,48	0,96	1,92

When summing up all the CRMs contained in the different Quantum Devices together, the following numbers as shown in Table J2.4 could be aggregated. Additionally below Figure J2.1 – J2.5 show the development of the CRM amounts over time.

Table J2.4: Aggregated data of CRMs contained in Quantum Devices under a slow rollout scenario until 2050.

	Development over time (t)						
CRM	**2021**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Beryllium Be	0	0	0	0	0	0	0
Graphite C	0	0,001	0,001	0,002	0,005	0,01	0,02
Dysprosium Dy	0	0	0	0	0	0	0
Erbium Er	0	0	0	0	0	0	0
Gallium Ga	0	0	0	0,001	0,001	0,002	0,005
Germanium Ge	0	0,001	0,001	0,002	0,005	0,01	0,02
Holmium Ho	0	0	0	0	0	0	0
Indium In	0,001	0,002	0,004	0,008	0,02	0,03	0,07
Lithium Li	0	0,001	0,001	0,002	0,005	0,01	0,02
Niobium Nb	0	0,001	0,002	0,003	0,006	0,01	0,03
Phosphorous P	0,001	0,003	0,006	0,01	0,02	0,04	0,09
Praseodymium Pr	0	0	0	0	0	0	0
Silicon Si	0,01	0,03	0,07	0,13	0,27	0,53	1,07
Titanium Ti	0	0	0	0	0	0	0
Tungsten W	0	0	0	0,001	0,001	0,003	0,006
Natural Rubber	0,06	0,12	0,24	0,48	0,96	1,92	3,84

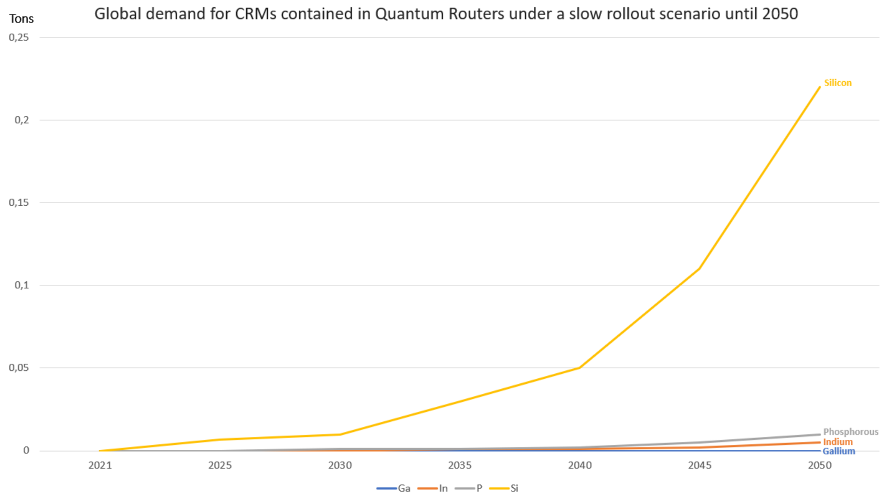


Figure J2.1: Demand development for CRMs contained in Quantum Routers under a slow rollout scenario until 2050.

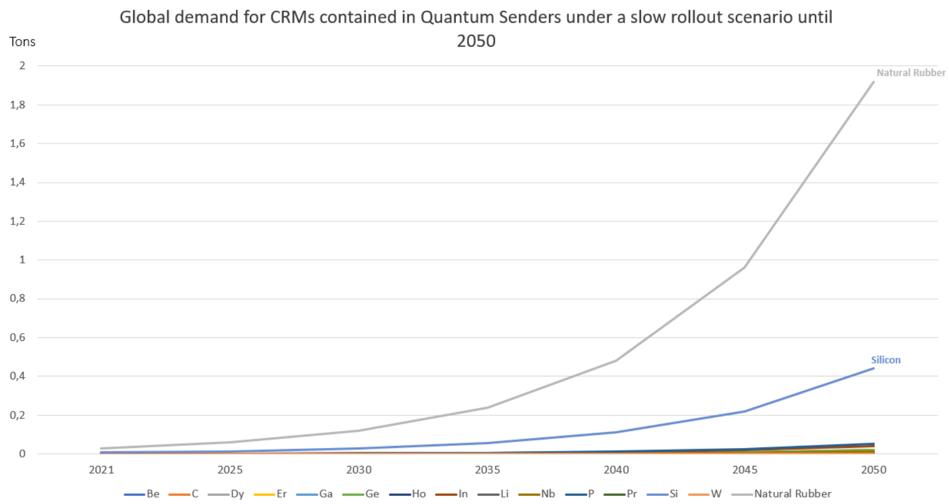


Figure J2.2: Demand development for CRMs contained in Quantum Senders under a slow rollout scenario until 2050.

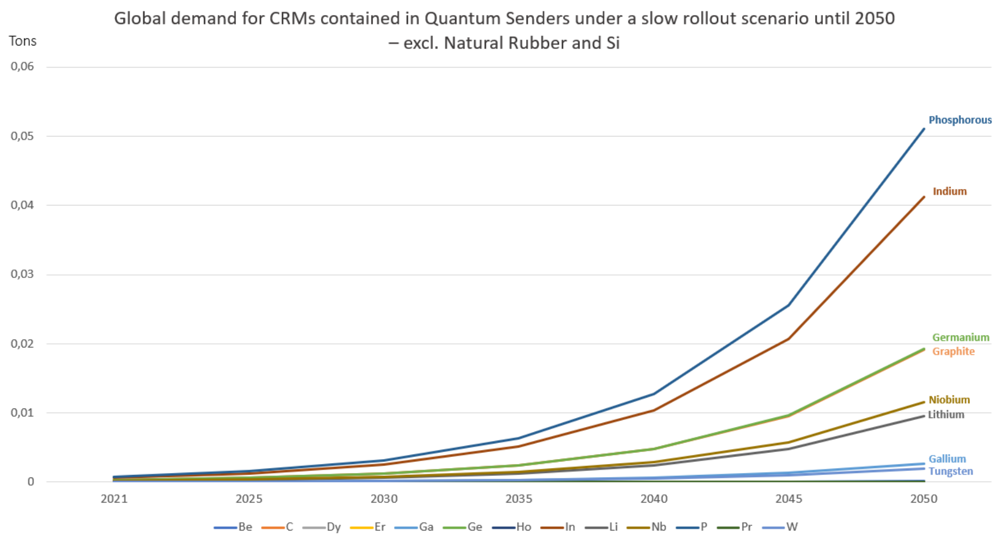


Figure J2.3: Demand development for CRMs contained in Quantum Senders under a slow rollout scenario until 2050 – Excluding Natural Rubber and Si.

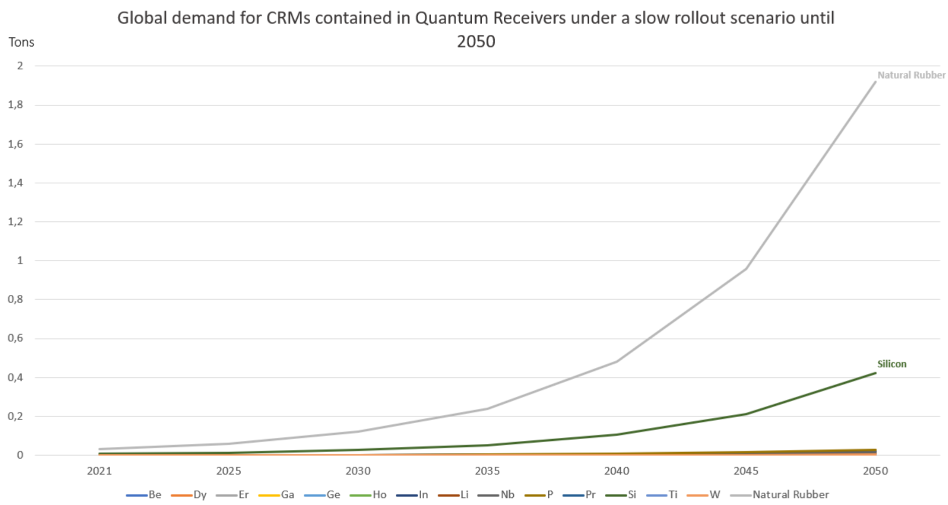


Figure J2.4: Demand development for CRMs contained in Quantum Receivers under a slow rollout scenario until 2050.

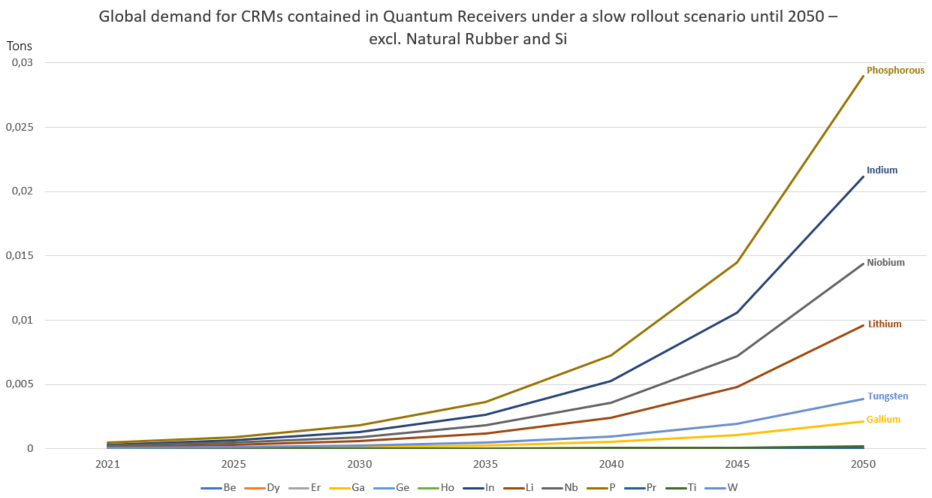


Figure J2.5: Demand development for CRMs contained in Quantum Receivers under a slow rollout scenario until 2050 – Excluding Natural Rubber and Silicon.

The demand development can be found in Figure J2.6 – J2.7.

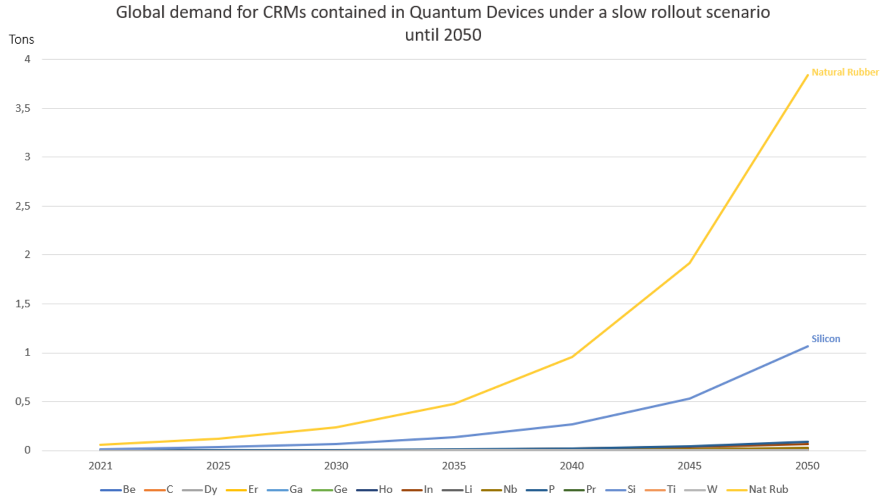


Figure J2.6: Global demand development for CRMs contained in Quantum Devices under a slow rollout scenario until 2050.

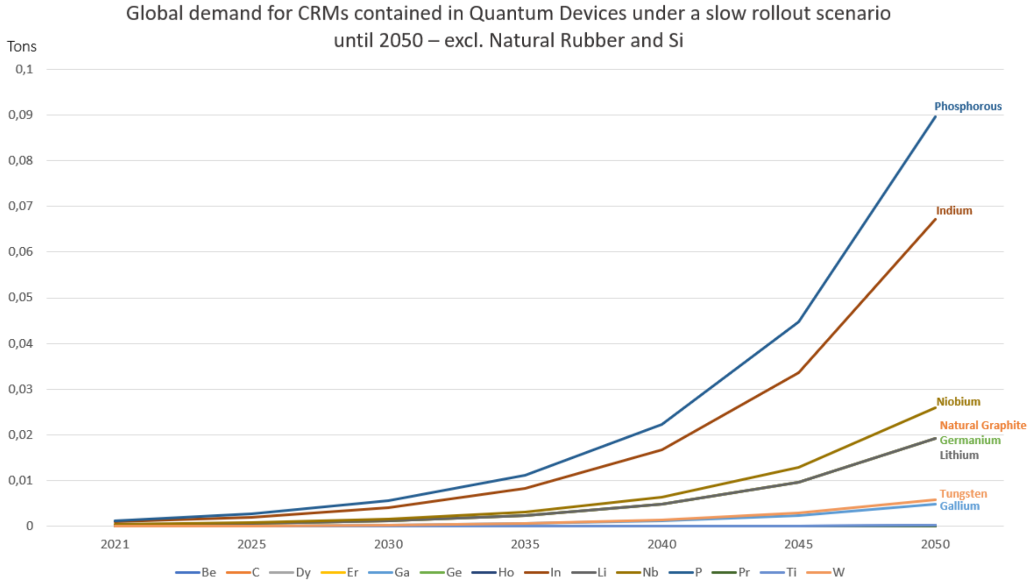


Figure J2.7: Global demand development for CRMs contained in Quantum Devices under a slow rollout scenario until 2050 – Excluding Natural Rubber and Si.

Scenario 2: Fast rollout of Quantum Technologies until 2050

Below Table J2.4 – J2.7 shows the raw data of the demand development under the fast rollout scenario until 2050. Figures J2.7 – J.10 show it graphically.

Table J2.4: Aggregated Weights of a Quantum Router under a fast rollout scenario.

Weight per CRM		Development over time (t)						
CRM	**Weight (g)**	**2021**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Gallium Ga	0,005	0	0	0	0	0	0,002	0,007
Indium In	0,5	0	0,001	0,002	0,008	0,04	0,17	0,72
Phosphorous P	1	0	0,001	0,004	0,02	0,08	0,33	1,44
Silicon Si	21	0	0,03	0,08	0,3	1,58	6,93	30,24

Table J2.5: Aggregated Weights of a Quantum Sender under a fast rollout scenario.

Weight per CRM		Development over time (t)						
CRM	**Weight (g)**	**2021**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Beryllium Be	0,011	0	0	0	0,001	0,004	0,02	0,07
Graphite C	1	0,001	0,004	0,02	0,08	0,33	1,44	6,3
Dysprosium Dy	0,001	0	0	0	0	0	0,001	0,006
Erbium Er	0,001	0	0	0	0	0	0,001	0,006
Gallium Ga	0,14	0	0,001	0,002	0,01	0,05	0,2	0,89
Germanium Ge	1,001	0,001	0,004	0,02	0,08	0,33	1,44	6,31
Holmium Ho	0,001	0	0	0	0	0	0,001	0,006
Indium In	2,15	0,003	0,008	0,03	0,16	0,71	3,1	13,55
Lithium Li	0,5	0,001	0,002	0,008	0,04	0,17	0,72	3,15
Niobium Nb	0,6	0,001	0,002	0,009	0,05	0,2	0,86	3,78
Phosphorous P	2,66	0,003	0,01	0,04	0,2	0,88	3,83	16,76
Praseodymium Pr	0,001	0	0	0	0	0	0,001	0,006
Silicon Si	23	0,03	0,09	0,35	1,73	7,59	33,12	144,9
Tungsten W	0,1	0	0	0,002	0,008	0,03	0,14	0,63
Natural Rubber	100	0,12	0,39	1,5	7,5	33	144	630

Table J2.6: Aggregated Weights of a Quantum Receiver under a fast rollout scenario.

Weight per CRM		Development over time (t)						
CRM	**Weight (g)**	**2021**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Beryllium Be	0,001	0	0	0	0	0	0,001	0,006
Dysprosium Dy	0,001	0	0	0	0	0	0,001	0,006
Erbium Er	0,001	0	0	0	0	0	0,001	0,006
Gallium Ga	0,11	0	0	0,002	0,008	0,04	0,16	0,69
Germanium Ge	0,001	0	0	0	0	0	0,001	0,006
Holmium Ho	0,001	0	0	0	0	0	0,001	0,006
Indium In	1,1	0,001	0,004	0,02	0,08	0,36	1,58	6,93
Lithium Li	0,5	0,001	0,002	0,008	0,04	0,17	0,72	3,15
Niobium Nb	0,75	0,001	0,003	0,01	0,06	0,25	1,08	4,73
Phosphorous P	1,51	0,002	0,006	0,02	0,11	0,5	2,17	9,51
Praseodymium Pr	0,001	0	0	0	0	0	0,001	0,006
Silicon SI	22	0,03	0,09	0,33	1,65	7,26	31,68	138,6
Titanium Ti	0,01	0	0	0	0,001	0,003	0,01	0,06
Tungsten W	0,2	0	0,001	0,003	0,02	0,07	0,29	1,26
Natural Rubber	100	0,12	0,39	1,5	7,5	33	144	630

Table J2.7: Aggregated data of CRMs contained in Quantum Devices under a fast rollout scenario until 2050.

Development over time (t)							
CRM	**2021**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Beryllium Be	0	0	0	0,001	0,004	0,02	0,08
Graphite C	0,001	0,004	0,02	0,08	0,33	1,44	6,3
Dysprosium Dy	0	0	0	0	0,001	0,003	0,1
Erbium Er	0	0	0	0	0,001	0,003	0,01
Gallium Ga	0	0,001	0,004	0,02	0,08	0,36	1,58
Germanium Ge	0,001	0,004	0,02	0,08	0,33	1,44	6,31
Holmium Ho	0	0	0	0	0,001	0,003	0,01
Indium In	0,04	0,01	0,05	0,25	1,11	4,85	21,2
Lithium Li	0,001	0,004	0,02	0,08	0,33	1,44	6,3
Niobium Nb	0,002	0,005	0,02	0,1	0,45	1,94	8,51
Phosphorous P	0,005	0,02	0,07	0,33	1,45	6,33	27,71
Praseodymium Pr	0	0	0	0	0,001	0,003	0,01
Silicon Si	0,05	0,2	0,76	3,69	16,43	71,73	313,74
Titanium Ti	0	0	0	0,001	0,003	0,01	0,063
Tungsten W	0	0,001	0,005	0,02	0,1	0,43	1,89
Natural Rubber	0,24	0,78	3	15	66	288	1260

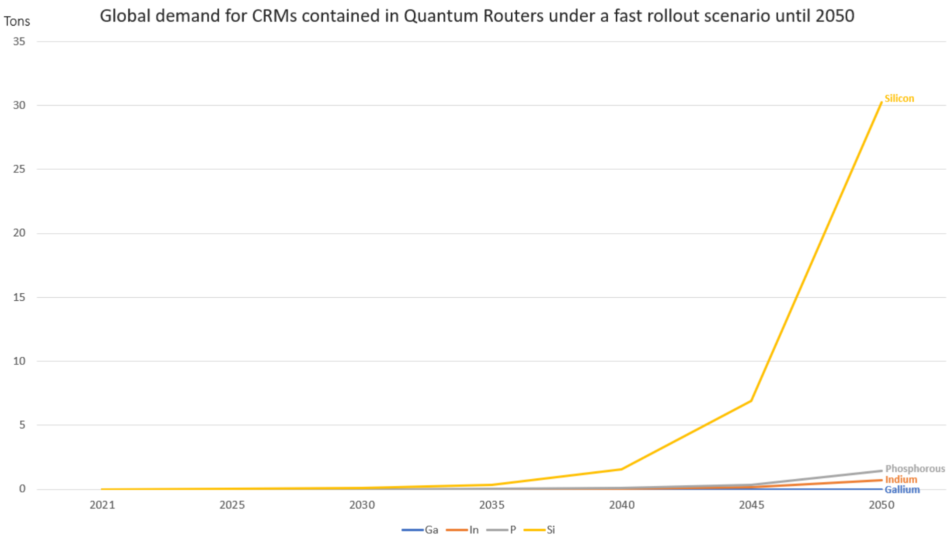


Figure J2.7: Demand development for CRMs contained in Quantum Routers under a fast rollout scenario until 2050.

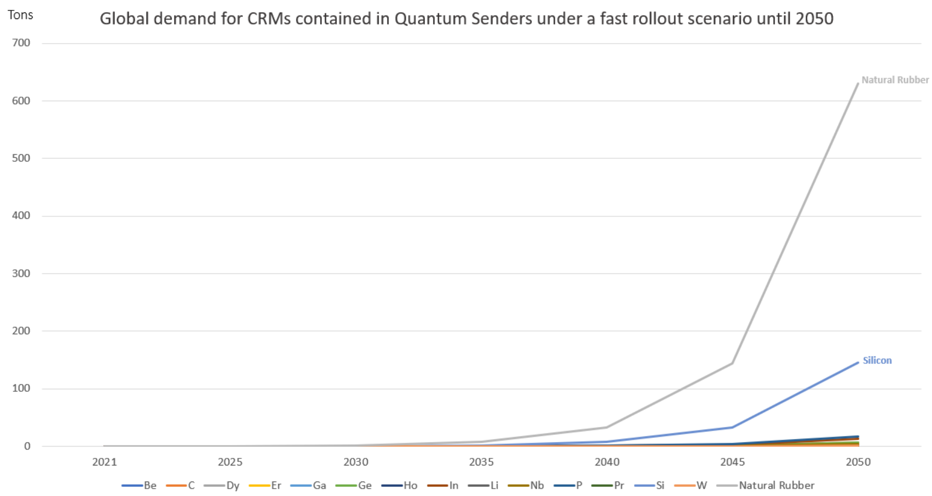


Figure J2.8: Demand development for CRMs contained in Quantum Senders under a fast rollout scenario until 2050.

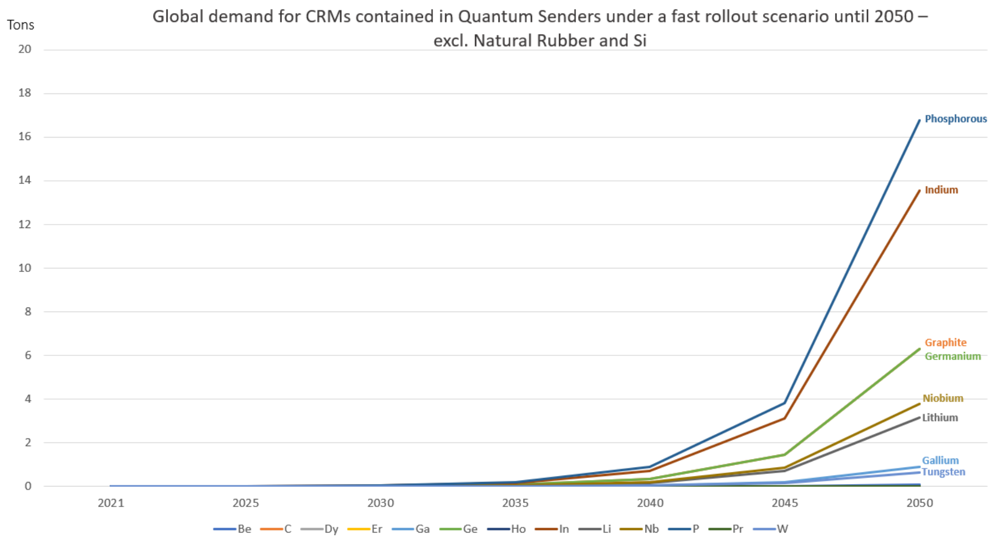


Figure J2.8: Demand development for CRMs contained in Quantum Senders under a fast rollout scenario until 2050 – Excluding Natural Rubber and Si.

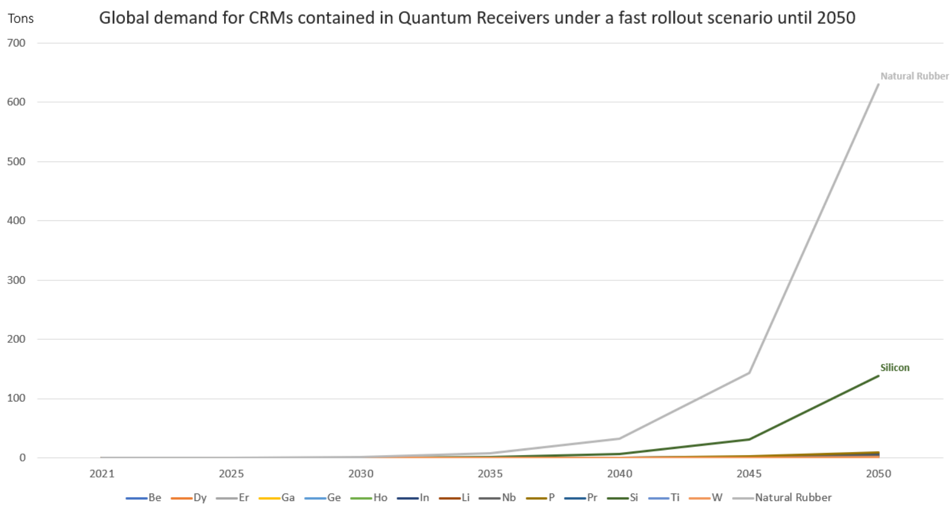


Figure J2.9: Demand development for CRMs contained in Quantum Receivers under a fast rollout scenario until 2050.

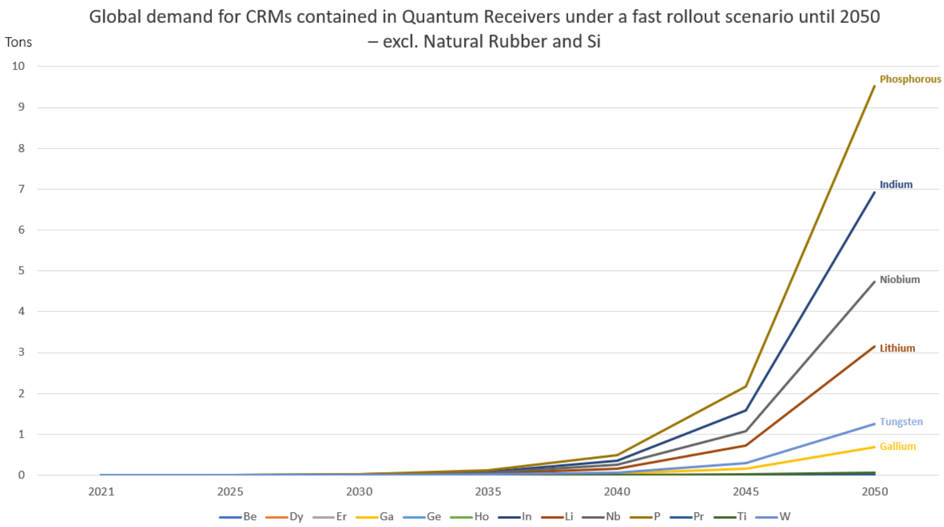


Figure J2.10: Demand development for CRMs contained in Quantum Receivers under a fast rollout scenario until 2050 – Excluding Natural Rubber and Silicon.

The demand development can be found in Figure 53 – 54.

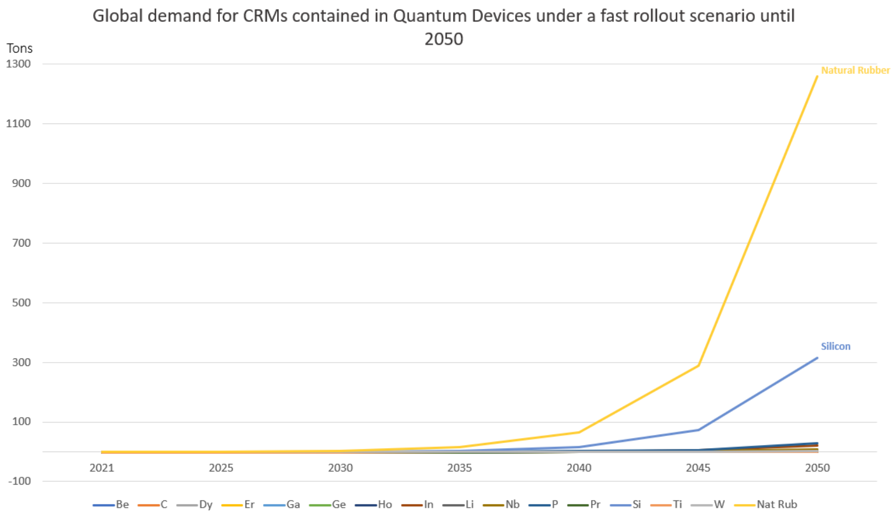


Figure 53: Global demand development for CRMs contained in Quantum Devices under a fast rollout scenario until 2050.

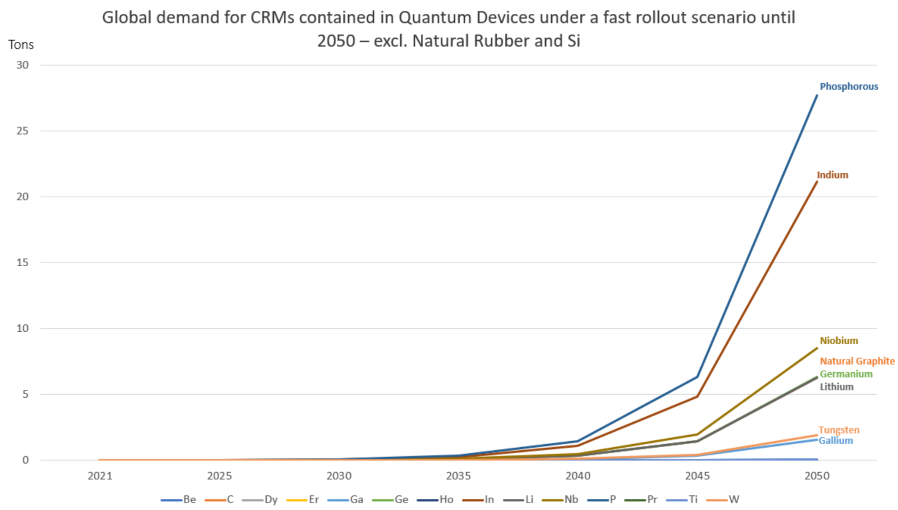


Figure 54: Global demand development for CRMs contained in Quantum Devices under a fast rollout scenario until 2050 – Excluding Natural Rubber and Si.

Appendix Chapter 6: Demand in the perspective of current supply

Appendix K: Current World Annual Production Rates

Below Table 71 shows the underlying data for the comparison of demand arising from CRMs contained in future telecommunication technologies and the current supply.

Table 71: Annual world production rates in future telecom technologies contained CRMs in 2020 according to USGS (2021).

In metric tons	Annual World Production	Year	Source	Notes
Antimony Sb	153.000	2020	USGS (2021)	
Barium Ba	7.500.000	2020	USGS (2021)	
Beryllium Be	240	2020	USGS (2021)	
Bismuth Bi	17.000	2020	USGS (2021)	
Boron B	3.630.000	2020	USGS (2021)	Inconsistent reporting makes it not possible to properly calculate the world production (USGS, 2021), but approximate number was taken as part of this report.
Carbon C (Graphite)	1.100.000	2020	USGS (2021)	
Cesium Ce	45	2018	Earth Magazine (2018); USGS (2021)	
Cobalt Co	140.000	2020	USGS (2021)	
Dysprosium Dy	100	NA	Lenntech (2021a)	
Erbium Er	500	NA	Lenntech (2021b)	
Gallium Ga	300	2020	USGS (2021)	
Germanium Ge	130	2020	USGS (2021)	
Hafnium Hf	70	NA	Edison (2019)	No clear data available due to connection to the nuclear industry and thus rough estimate (Edison, 2019).
Holmium Ho	10	NA	Mmta (2016a)	
Indium In	900	2020	USGS (2021)	
Lithium Li	82.000	2020	USGS (2021)	
Magnesium Mg	1.000.000	2020	USGS (2021)	
Neodymium Nd	7.000	NA	Elements Database (2015)	
Niobium Nb	78.000	2020	USGS (2021)	
Palladium Pd	210	2020	USGS (2021)	
Phosphorous P	/			
Platinum Pt	170	2020	USGS (2021)	
Praseodymium Pr	2.500	NA	Lenntech (2021c)	
Ruthenium Ru	12	NA	Lenntech (2021d)	
Samarium Sa	700	NA	Lenntech (2021e)	
Silicon Si	8.000.000	2020	USGS (2021)	
Strontium Sr	210.000	2020	USGS (2021)	
Tantalum Ta	1.700	2020	USGS (2021)	
Terbium Tb	10	2020	Lenntech (2021f)	
Thulium Tm	50	NA	Mmta (2016b)	
Titanium Ti	210.000	2020	USGS (2021)	
Tungsten W	84.000	2020	USGS (2021)	
Vanadium V	86.000	2020	USGS (2021)	
Yttrium Y	10.000	2020	USGS (2021)	
Fluorspar	7.600.000	2020	USGS (2021)	

Natural Rubber	13.000.000	2020	Statistica (2021)	
Phosphate Rock	223.000.000	2020	USGS (2021)