UNIVERSITY OF LJUBLJANA

SCHOOL OF ECONOMICS AND BUSINESS

MASTER THESIS

SUSTAINABILITY STRATEGIES FOR MITIGATING THE SUPPLY CHAIN RISK FOR SMART METERS

Ljubljana, September 2022 NATASHA STAVREVSKA

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LIST OF ABBREVIATIONS

EU – European Union

TOPSIS - Technique for Order of Preference by Similarity to Ideal Solution

SC – Supply Chains

IT- Information Technology

OEM - Original Equipment Manufacturers

EBITDA - Earnings before Interest, Taxes, Depreciation, and Amortization

PGM - Platinum Group of Metals

REE - Rare Earths Elements

LE - Linear Economy

CE - Circular Economy

LCA - Life Cycle Assessment

KPI – Key Performance Indicator

UM - Urban Mining

LFM - Landfill Mining

UMDBC - Urban Mining Demonstration Base Construction

NACE - Nomenclature of Economic Activities

EOL – RIR - End-of-Life Recycling Rate of Input

PSAV - Political stability and absence of violence/terrorism

HHI - Herfindahl–Hirschman index

USGS - United States Geological Survey

MCDA - Multi-Criteria Decision Analysis

GeoPolRisk - Geopolitical Supply Risk

PCB- Printed Circuit Board

Li-ion - Lithium-ion

LIB - Lithium Ion Battery

INTRODUCTION

Organizations that manage electronic components have been dealing with a series of part shortages, price increases, and longer lead times. The ability to satisfy demand became a difficult task, especially for more basic passive components like resistors, diodes, transistors, and even memory, due to a large rise in demand on one hand and severe materials and parts scarcity on the other. Before the epidemic, suppliers were stating lead times of 20-30 weeks on average (Scott, 2021). When the Covid-19 epidemic hit in the spring of 2020, the shortage just accelerated, and the uncertainty increased as well. As a result of globalization, geopolitical issues play a significant role in the disruptions of supply chains. Many of the minerals and components used in electronics are extracted and made in China, the first nation to undertake a lockdown to stop the spread of the Covid-19 epidemic. During the SARS pandemic, the same problem was witnessed in the computer manufacturing industry, as many of the affected assembly lines were also based in China (Althaf & Babbitt, 2021). The criticality of materials is becoming a problem for manufacturers, policymakers, and other stakeholders. Concern over the supply of some metals and minerals has arisen due to factors like the uneven geographical distribution of mineral reserves and extraction sites worldwide, the desire to move away from the use of conventional sources of electricity, and unstable world politics. (Moats, Alagha, & Awuah-offei, 2021).

According to the European Commission, Europe must recognize the potential of digital transformation, which can help achieve the goals and initiatives of the Green Deal, whose aim is to reach a climate-neutral Europe by 2050 (Maguire, 2021). This perspective emphasizes how the twin ecological and digital transformations will touch every aspect of our economy, society, and industry. According to the International Renewable Energy Agency’s assessment, energy-related carbon-dioxide emissions must be reduced by 70% by 2050 compared to today’s levels to fulfil climate targets. New green technology is currently available to assist in addressing this problem. Renewable energy sources, such as solar and wind, have the potential to satisfy 86% of electricity demand in 2050. (International Renewable Energy Agency, 2019). The green and digital transitions need to support one another. For instance, distributed ledger technology, which powers blockchain technology and cryptocurrencies, may be applied to material tracing to improve maintenance and recycling, which will benefit the circular economy. Digital Twins, which are virtual replicas of the actual world, may mimic a variety of things, including traffic, to optimize traffic patterns and lower emissions overall (Joint Research Center, 2022).

Energy demand management may be an effective strategy for reducing energy use, therefore smart metering is perceived as a key enabler of the energy transition, as well as a driver of digitalization and energy efficiency (Coelho et al., 2019). Smart meters are products that depend on electronic components and are directly competing with all industries that use electronic components. Disruptions in the supply chains are already happening, so expanding and exploring the possible risks for the future is inevitable and a necessity.

In order to manage the resource risk, companies need to carefully plan their sourcing strategies. The purpose of this thesis is to explore and map the risks related to the components of the smart meter, to get an overview of what areas are most critical, and what is possible to do to deal with potential disruptions in the supply chains in the future. The goal of the thesis was to use the literature and already existing risk assessment tools in practice, in the example of a smart meter manufacturer, and fill the gap of known risks by broadening the scopes of risk and how they interdepend on each other. This master thesis consists of three parts, described below.

The first part is a theoretical overview of supply chain risk management, the risk management process, and the particularities of supply chains in the electronic industry. A detailed overview was done on the critical and conflict materials, with a focus on the environmental impact, future legislations, and the impact they will have, as well as the opportunities related to these materials and their importance in the smart metering industry. Circular economy as a concept is explained and sustainable activities that can be implemented to achieve circular economy are defined. After the literature review, a decision was made to put the focus on the first step of the supply chain i.e., the raw materials. For the analysis of the risk related to selected raw material, I applied the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), a multi-criteria decision analysis method.

The second part is dedicated to the collection and structuring of the data used, and the implementation of a method to map and identify the risks of the raw materials. Existing parameters and indexes were used, such as global reserve, market concentration, price volatility, annual mine production, global warming potential, cumulative energy demand, etc.

The third part consists of an analysis of the results, as well as exploring how sustainable mitigation strategies like recycling, reusing, and urban mining are implemented already and their potential in the future. Connection to the components of a smart meter is made with the risk scores calculated in the second part.

1 LITERATURE REVIEW

1.1 Risk management in supply chains

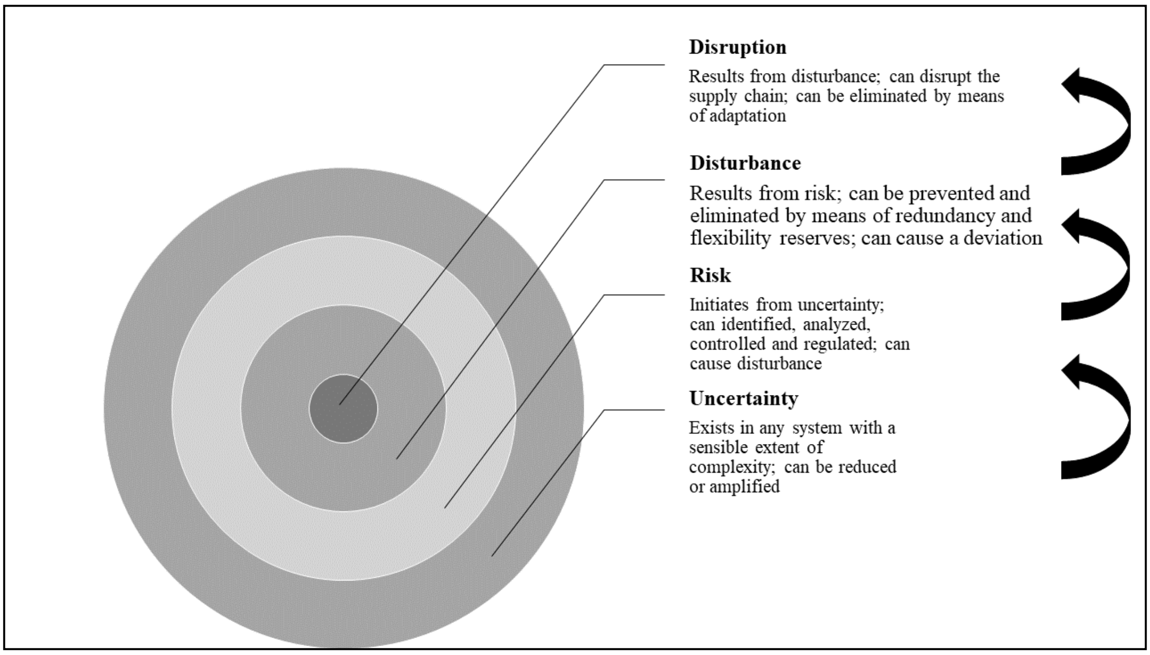
Uncertainty exists in every business process and decision. Because incorrect evaluations and judgments can lead to unanticipated events that might have serious implications if identified too late, uncertainties must be continually monitored and handled. The relevance of risk concerns has increased in tandem with the rising number of important uncertainties. Despite (or maybe because of) its lengthy history, the term risk remains ambiguous and sometimes inadequately defined (Heckmann, Comes, & Nickel, 2015).

Some researchers define uncertainty as an attribute that describes how little we know about the system and the circumstances surrounding its emergence. Risk is a notion that has many different definitions. One would be drawn from the history, others categorized the "measurable" uncertainty as "risk." Risk is the variation of return, according to researchers who studied finance. Risk may be described as a measurement of the likelihood and impact of not reaching a certain project goal. Also, risk is defined as a function of the likelihood that a negative event will occur and the magnitude of the resulting damage (Ivanov, Tsipoulanidis, & Schönberger, 2019). Risk is often defined as the set of potential (unfavorable) outcomes from a particularly rational decision and their probabilistic values. The word "vulnerability," is used in place of "risk" in supply chain management literature (Gurtu & Johny, 2021).

One overarching definition of risk management is offered by the Council of Supply Chain Management Professionals as: “The identification, evaluation, and ranking of the priority of risks followed by synchronized and cost-effective application of resources to lessen, monitor, and control the probability and/or impact of unfortunate events” (Council of Supply Chain Management Professionals, 2013).

Having established that risk can be defined differently depending on the area it is affecting, the situation it is being analyzed and what value is being threatened, the reality is that risk exists and will exist as long as some processes or activities are in place. For companies and institutions to cope with risk, risk management should be employed as part of their structure. Four factors are typically encountered while analyzing uncertainty and risks. The first and second are already discussed - uncertainty and risk, followed by perturbation influence (disturbances) and perturbation impact influences (deviations). For every system with a reasonable complexity level, uncertainty is a basic component of a system that exists independently of us. It can be widened and reduced the uncertainty space, as seen in Figure 1 and risk comes from uncertainty. Risks can be detected, assessed, monitored, and regulated.

Figure 1. Cross relations of uncertainty, risk, disturbance, and disruption



Adapted from Ivanov, Tsipoulanidis & Schönberger (2019, p. 457).

The consequence of risk is a disturbance (perturbation impact). Both intentional (i.e., thefts) and accidental (i.e., demand fluctuations or the occurrence of a particular situation that could demand changes in the supply chain) may occur. It may or may not lead to a deviation (disruption) in the supply chain, depending on how much the supply chain is robust and adaptive to overcome the disturbance. Influences from perturbations lead to operational deviations and affect processes, plans, and targets. Adaptation measures must be taken in the event of deviations (Ivanov, Tsipoulanidis & Schönberger, 2019).

Over time, academics and business professionals have come to understand the value of supply chain and purchasing management strategies in improving organizational efficiency. They are interrelated and strategically important for market competitiveness. As a consequence of reduced product lifetime, globalization, and preferences of end users, many supply chains have encountered unplanned volatility in recent years.

The origin of risks is an important attribute to have to distinguish between different types of risk, which might come from within the chain or from the outside environment. Endogenous risk is when the source of risk is internal to the supply chain and can change the connections between the focal company and its suppliers (Trkman & McCormack, 2009). This type of risk is also called internal risk, and because it is within a firm's control, it offers higher opportunities for mitigation. Examples of such risks include production risks related to disruptions in internal operational activities, and business risks - brought on by changes in key employees, managers, reporting, and knowledge transfer practices. Some processes can be also a source of risk, for instance, how employees communicate with suppliers. Monitoring risks - caused by lack of planning and evaluation leading to poor management, and contingency risks, which happen because of failing to implement contingencies or alternatives in case something happens unexpectedly (Fu & Zhu, 2019).

Exogenous risk is when the source of risk or uncertainty is external to the supply chain (Trkman & McCormack, 2009). Such examples are demand risks - induced by unpredictability or misinterpretation of customer or end-customer demand, supply risks - caused by any disruptions in the flow of product, whether raw materials or parts, inside the supply chain, and environmental risks - from outside the supply chain, often connected to economic, social, governmental, and climate issues, including the danger of terrorism, physical plant risks - caused by the state of a supplier's physical facility and regulatory compliance and finally business risks - caused by variables such as a supplier's financial or managerial stability, or the purchase and sale of supplier firms (Bode, Kemmerling, & Wagner, 2013).

Further classifying of these risks is done into two categories, namely discrete occurrences (such as terrorist attacks, contagious illnesses, and worker strikes) and continuous risks (such as fluctuations in the inflation rate and consumer price index), which are connected to the way that risk is distributed concerning the probability distribution of its impact (Trkman & McCormack, 2009). A typical example of continuous risk is price adjustments for raw materials. Events when the costs of anticipated changes are continuous and very straightforward to estimate. For these risks, it is possible to calculate the impact of price increases on profit margins and make early arrangements for various insurance products, such as forward and future contracts that can reduce price volatility (Kromoser, Mayer, & Kaltenbrunner, 2021). On the other hand, discrete events comprise high-impact occurrences that may be categorized as acts of terrorism, the spread of illnesses, and natural disasters. Political upheavals like those in Venezuela or Myanmar can also be disruptive (BBC News, 2021; European External Action Service (EEAS), 2021). Transport interruptions at other points throughout the chain might potentially result in significant delays or delivery failures. The covid-19 pandemic is the most recent event that was difficult and not possible to foresee, and the effects are significant yet difficult to quantify (Gardt, Angino, Mee, & Glöckler, 2021). However, the frequency of such occurrences may frequently be anticipated (e.g., hurricanes in the Gulf of Mexico in the summer or major snowstorms in the Alps in the winter are quite likely), and as a result, should be considered when calculating risk scores (Trkman & McCormack, 2009). Table 1 shows many examples of possible disruptive events, divided into four categories.

Table 1. Categories and examples of disruptive events

Category	Disruptive event
Catastrophic events/Macro level risks	Natural disasters (e.g. earthquake, flood, strong wing, fire, hurricanes, tsunami); International terror attacks; Political instability, mass killing, war, civil unrest or other sociopolitical crises, economic crisis; Diseases or pandemics (e.g. SARS, Covid-19); Environmental incident (e.g. pollution, waste management); Legal, regulatory, labor, financial and bureaucratic events; New laws, rules or regulations (e.g. new tariff rates); Political factors and administrative barriers for the setup or operation of supply chains (e.g. authorization from governments for oil extraction); Currency exchange rate volatility; Human resource related events (e.g. Loss of talent/ skills, illness, health & safety incidents); Business ethics incidents (e.g. human rights, corruption, Intellectual Property violation).
Demand-side events	Unanticipated or highly volatile customer demand, rush orders; Insufficient or distorted information from customers about orders or demand quantities, delivery, coordination, and sourcing constraints (bullwhip effect).
Supply-side events	Supplier/Outsourcer failure (e.g. bankruptcy, company buyouts, deliberate sabotage); Supplier product quality problems (e.g. product recall, rejected parts); Sourcing constraints (dependability, energy or natural resources scarcity, insufficient supplier capacity)
Logistics–Transportation events	Poor logistics performance of suppliers (delivery delay, order fill capacity, parts misplaced in the plant, poor delivery coordination); Poor logistics performance of logistics service providers (LSP) (scheduling errors, mislabeled parts, non-optimal transport route selection); Transport network disruption (caused by traffic, weather, customs delays, demonstrations); Equipment failures (truck, railroad, ship, port cargo- handling, and rail yard); Customs clearance, permit, and inspection delays at borders.
Production-Infrastructural events	Loss of own production capacity due to technical reasons (e.g. equipment breakdown, IT infrastructure failure, machine deterioration); Unplanned IT or telecommunications outage; Downtime or loss of own production capacity due to local disruptions (e.g. labor strike, fire, explosion, industrial accidents, gas leakage); Cyber-attack and data breach.

Adapted from Katsaliaki, Galetsi, & Kumar (2021, p. 8)

Some risks can be detected, evaluated, and managed. Such an example would be delayed or canceled delivery of goods because a supplier filed for bankruptcy. What is the probability of such a disruption happening is estimated using the previous financial activity of the supplier. Emerging risks such as cybersecurity breaches, are now easier to quantify thanks to an external examination of an IT infrastructure, done by third parties, to measure cybersecurity potential vulnerabilities. Because these kinds of risks can be predicted and assessed, they are called known risks.

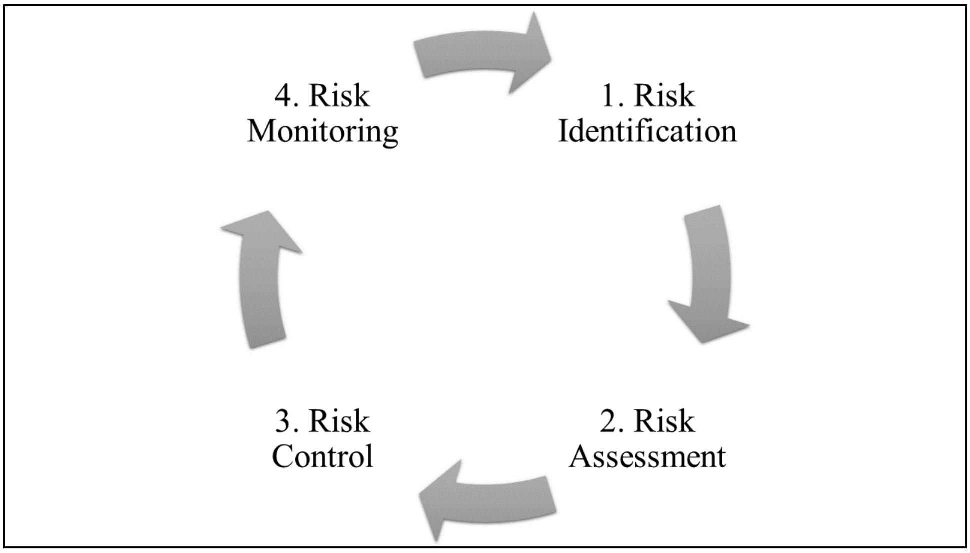
Organizations should spend time working with a cross-functional team to classify the entire range of risks they face, by developing a risk-management framework that identifies which metrics are suitable for measuring risks, what is the "best case" for each metric, and how to rigorously track and oversee these metrics. This team can also recognize gray zones where threats are difficult to comprehend or describe, in cases when parts of the supply chain have no visibility. This approach can help to visualize the magnitude and extent of unknown risks.

Unknown risks are those that are impossible or extremely difficult to anticipate. An abrupt eruption of a long-dormant volcano, which disturbs activity related to a supplier that was not in the immediate parts of the supply chain, or the exploitation of a cybersecurity weakness hidden deep within the firmware of a vital electrical component. Even the most risk-averse managers will find it difficult to predict events like this. As mentioned before, the Covid-19 pandemic and the effects it had on the global supply chains and the shortage of electronic components. However, when it comes to unknown risks, lowering their likelihood and enhancing the speed with which they may be recognized and mitigated is crucial to maintaining a competitive edge. Creating strong layers of protection in conjunction with a risk-aware culture can provide a firm with this advantage (Bailey, Barriball, Dey, & Sankur, 2019).

1.2 Risk management process

One of the most comprehensive explanations of the steps in the risk management process is offered by Zwiler & Herm (2012). Figure 2 depicts the steps in the risk management process. The different phases are detailed in further depth below.

Figure 2. Steps of the risk management process



Adapted from Zwiler & Herm (2012, p. 469).

- Risk identification

The identification of risks is the beginning point. It is sometimes referred to be the most critical phase since only detected risks may be included in the risk management framework and handled by suitable strategies. Every undetected risk increases the likelihood of interruptions and, in the worst-case scenario, losses that jeopardize the business's future. As a result, the first step is to identify possible dangers early on and document them in a structured way (Crispin, 2020).

- Risk assessment

The identification of risks is followed by risk assessment. In this stage, risks are evaluated in terms of their likelihood of occurrence and possible level of impact. The two dimensions can be described qualitatively as well as quantitatively. Experts' estimations and fault tree analysis are examples of qualitative approaches for determining the likelihood of occurrence, whereas quantitative procedures are based on a statistical analysis of previous data or simulation models to determine adverse variations in sales, profit margins, or operational expenses (Aven, 2016).

- Risk control

Risk control is the next step following a risk assessment. Specific risk-management strategies are used at this level. There are two kinds of measures defined by Zwiler & Herm (2012) - proactive measures that are designed to avoid or mitigate risks, whereas reactive measures address what has to be done if losses occur:

- Taking proper precautions to avoid a known risk. This is undoubtedly the ultimate aim, albeit the cost-benefit connection should be considered. Measures and strategies should and may be adopted as part of supply chain risk management if this is correctly balanced.
- Taking necessary efforts to mitigate an identified risk. If a risk cannot be avoided, it should be minimized
- Taking necessary measures to limit or transfer a detected risk. This approach assists in the reduction of risks and potential consequences. If a risk happens, even if it occurs at the supplier's location, your organization may be indirectly impacted. As a result, if at all feasible, this strategy should be abandoned.
- Sharing a detected risk by taking appropriate measures. The measure's impact should be that entrepreneurial activities are shared throughout supply chain stakeholders. This guarantees that the repercussions of a risk if it arises, have a far smaller impact on the individual parties.
- Accepting a risk and taking precautionary measures. If the risk cannot be completely avoided or if one of the aforementioned strategies cannot be used, this is the way to go. A corporation voluntarily accepts residual risk, knowing full well that it may occur, but concluding that the consequences are justified in comparison to the cost or expenditure of decreasing or even preventing the risk (Zwiler & Herm, 2012).

- Risk monitoring and documentation

The risk documentation and monitoring phase is considered a continuous element of risk management, executed in parallel with the preceding stages. A risk documentation system, above all, provides an overview of identified risks, details all risk mitigation measures already in place, and tracks implementation progress. For risk documentation, an IT-based platform is recommended. Furthermore, documentation must allow a centralized risk management unit to monitor and regulate all risk management procedures (Metheny, 2017).

1.3 Risks in the electronic component supply chains

In contrast to other industries, the electronics sector covers a diverse set of products. When consumers think of this industry, it is natural to think of the products that surround us like phones and computers. The reality is much different, as the electronic industry is broadly classified as the production of electronic equipment, instruments, network and telecommunication components, various hardware devices, etc. The electronics sector is largely concerned with the interconnection of technologies to provide the desired product for its customers (Lockamy, 2019).

The electronics business has high-value commodities, a high rate of obsolescence, high demand and supply volatility, and broad product diversity. As a result, there is a danger of having an excess or insufficient amount of inventory. Furthermore, longer lead times, seasonal demand, a wide variety of products, quality concerns, counterfeit components in subassemblies, and changes in client preferences have increased tremendously in the electronics sector, making the electronic supply chain vulnerable to different SC risks (Ramesh, Sarada, & Pradeep, 2020).

Recent natural disasters, such as the floods and earthquakes in Asia, have caused several large electronics corporations to either delay or close their production plants mainly due to the lack of memory chips and hard disks, causing supply disruption for many of the electronics manufacturing industries. Many times companies create overreliance on providers of material and assembly of components, as well as the decisions on financial and technology investments are trusted upon suppliers, which contributes to the electronic supply chain's exposure to supply risks (Gunessee, 2018). The electronic supply chain has a direct influence on the development of any country. In many countries, the electronics sector is one of the top five industries that contribute to the country's economic growth (Almajali, Mansour, Masa’deh, & Maqableh, 2016). Inbound supply risks in the electronic supply chain will probably increase because of strict emission and green criteria created by European Union (EU) for suppliers, which will be discussed in the next chapter.

The greatest challenge in the complex electronics supply chain is anticipating component shortages. Supply chain disruptions may cost electronics firms a 3.9 percent EBITDA loss yearly, according to the McKinsey Global Institute. It is simply impossible to manually control supply chain risks as they grow in number. Global firms may detect supply chain risks and manage them proactively to respond more quickly and prevent or mitigate shortages. Companies may become risk-conscious and improve their decision-making through comprehensive risk management, which includes supplier risk assessment and cooperation. Automation of supply chain risk management may help electronics manufacturing companies and their partners maintain their profits, gain competitive advantage, and increase resilience (Lund et al., 2020).

Electronics supply chains are extremely risky due to manufacturers' reliance on highly specialized partners. At the same time, several high-impact risks make it difficult to prevent interruptions (Vakil & Linton, 2021). The biggest risk factors impacting electronics manufacturing are often supplier networks in areas vulnerable to natural disasters and geopolitical turmoil (Althaf & Babbitt, 2021). But even so, the industry as a whole lacks transparency into a big supplier base that includes influential key players, and which frequently has large numbers of sub-tier suppliers. Handling compliance risks is extremely difficult due to the complex regulatory frameworks in materials sourcing, electronics production, and vertically integrated sectors. These kinds of factors could develop into weak links that endanger efficiency, supply, and ultimately the company's capacity to thrive if real-time insights into the supply chain are not achieved (Delloite, 2012).

One particularity for the electronics supply chain is related to some elements/metals that are susceptible to supply risks because of activities inside a complex supply chain of which they are part. For instance, selenium and tellurium production is influenced by factors that drive copper production and research, whereas indium and germanium production is influenced by the zinc supply chain (Nuss & Eckelman, 2014). Another issue that makes these elements critical is that the current manufacturing practices, particularly in electronics, utilize these materials in ways and quantities that make recycling or substituting problematic. For instance, a large amount of worldwide tellurium output from manufacturing is lost to the environment due to dissipative usage (Moats et al., 2021). The following chapter presents the critical raw materials in the electronic industry and shows their interconnectedness.

2 CRITICAL RAW MATERIALS

The evaluation and list of critical raw materials are meant to alert the EU economy to the supply risk of important resources. They help to ensure the competitive advantage of EU industrialized value chains, beginning with raw materials, and following EU industrial strategy. It should also assist to incentivize European extraction and production of critical raw materials and make the start-up of new mining and recycling operations easier. The list of these materials is also used to assist in prioritizing goals and activities. It can be used to help negotiate trade agreements, challenge trade-distorting policies, or promote research and innovation initiatives. The materials that are on the list can vary from report to report, but even if some raw materials are not on the list, that doesn’t mean they are not as important, since they all play an essential part in the EU economy. Their availability to the EU economy ought not to be ignored solely because they are not classified as critical.

The importance of critical raw materials for the EU is widespread across many areas:

- In industrial value chains - raw materials are integrated into all sectors at all stages of the supply chain and their use is inevitable
- In digitalization - technical advancement and wellbeing depend on the innovation of devices and tools. They are dependent on raw materials and their physical availability.
- In green transition- raw materials are a necessity for low-carbon technologies like wind turbines, photovoltaics, and smart meters needed to reach carbon objectives by 2050. (European Commission, n.d.-b).

In Europe, the manufacturing and the metallurgy (refining) sector are sometimes seen as more significant than the extractive industry (mining activities). Furthermore, the European industry does not cover the whole value chain of raw materials, with a significant disparity between the upstream (extraction) and downstream processes (manufacturing and use). Nonetheless, the requirement for raw materials, such as ores and concentrates, as well as processed and refined resources, is critical for the wealth - and even survival of European businesses, as well as the employment and economy that they support. Relatively little non-energy raw material extraction happens within the European Member States, with most ore and concentrates, processed materials, or metals originating in non-European countries.

The EU is not present in the upstream stages of the value chain for numerous raw minerals, including antimony, beryllium, bismuth, borates, molybdenum, niobium, platinum group of metals (PGM), rare earth elements (REE), tantalum, titanium, vanadium, and zirconium. This could be due to a lack of mineral reserves in the EU, or, more commonly, a lack of knowledge about the extraction possibilities of those materials in the EU. Additionally, economic, and societal factors obstruct the estimation of resources and reserves, their discovery and characterization, or extraction, like closing already existing mines, unwillingness to open new mines, etc. To have access to these raw resources, European Member States must import them from other nations, either unprocessed or refined, to bring them to their businesses and markets. The only countries that produce large amounts are France, Spain, Portugal, and Greece, producing hafnium, strontium, natural cork, and perlite. Some raw minerals, such as gypsum, hafnium, indium, magnesite, silica sand, and sulfur, are produced in satisfactory quantities by the Member States preventing large out-of-Europe imports. However, this is a very unusual circumstance, with the EU relying on imports for more than 80% of the raw materials required by its industry and economy.

The dynamic technological advances and quick expansion of developing economies have resulted in an increased demand for a variety of metals and minerals. Achieving a continuous supply of such essential raw materials has proved to be a major problem for local and global economies with scarce natural resources on-hand, which is the case for Europe, which is heavily dependent on imports. China is the main supplier of several critical raw materials including bismuth, antimony, magnesium, and most rare earth elements. The likelihood of shortages and instability of the supply along the value chain is increased by this.

The possibility of supply disruption is exacerbated by the fact that all processes starting from extraction to smelting and refining of the metals are located in a small number of countries. Aside from this, some countries that hold this competitive advantage rigorously control and prohibit the export of raw materials to preserve their home industries by adopting export restriction policies that typically omit free markets. Supply constraints can have a detrimental impact on all supply chain participants because they affect supply conditions and price volatility. Mineral and metal mine production frequently relies on large-scale investment projects that can take many years to complete, making it difficult to respond quickly to short-term changes in demand or susceptible to market manipulation by established suppliers attempting to obstruct emerging mining operations.

These facts, when combined, raise the prospect of supply shortages for metals and minerals in the EU. The known resources in the EU are not being utilized effectively to deliver the appropriate and timely supply of these minerals to fulfill domestic demand. The consequence of an interruption in raw materials supply might thus be a loss of competitive economic activity in the EU, as well as reduced availability of certain (strategic) finished goods in some situations (Blengini et al., 2020).

2.1 Current and upcoming legislations in the European Union

Sustainability is no anymore just an “option” but a must approach for every company. A multi-stakeholder approach to sustainable development is critical for introducing new methods and tools for finance, innovation, and research. The economies around the world are speeding up with their sustainability projects and actions, aware that this will be an important benchmark among the competitors and important for brand reputation, access to finance, etc. (Moallemi et al., 2020).

To accomplish the EU's 2030 climate and energy targets, as well as the goals of the European Green Deal, the EU is steering investments toward sustainable initiatives and activities. The Covid-19 pandemic has highlighted the importance of redirecting funds to long-term initiatives that will make the economies, companies, and society more robust to climate and environmental disruptions. Hence, common terminology and understanding of what "sustainable" means are needed. As a result, the action plan for funding sustainable growth proposed the creation of a standard classification system for sustainable economic activity, also known as an "EU taxonomy." As a result, businesses must declare their sustainability performance to financial institutions. The EU taxonomy is a complicated method for categorizing which sectors of the economy may be marketed as sustainable investments. It covers a large list of economic activities as well as comprehensive environmental requirements that should provide investors with security, protect private investors from greenwashing, aid enterprises in becoming more environment friendly, reduce market fragmentation, and assist in shifting investments to where they are most needed (European Commission, 2020).

Another legislation that will be enforced is the Corporate Sustainability Reporting Directive, whose goal is to widen the scope of the Non-Financial Reporting Directive (NFRD). This directive is requiring large to provide information on how they operate and address social and environmental challenges. The extension to this consists of an audit (assurance) of reported information, introducing more detailed reporting requirements, and a requirement to report following mandatory EU sustainability reporting standards, demanding companies to digitally 'tag' the reported information, so it is machine-readable, and feeding into the European single access point envisaged in the capital markets union action plan. The first set of standards should be adopted by October 2022 (European Commission, n.d.-a).

The European Commission has adopted a proposal for a Directive on corporate sustainability due diligence in February 2022. The concept intends to promote ethical and sustainable corporate conduct throughout global value chains. Finding negative effects across the value chain will be simpler if corporations undertake due diligence and more information on negative consequences on human rights and the environment is available. The directive's scope is primarily centered and organized on the need to carefully assess corporate practices that harm human rights and the environment, which is explicitly stated in the relevant international treaties specified in the Annex. Directors of firms must be active to ensure that due diligence becomes a part of the whole operation of the company. Furthermore, the Directive requires every organization to have a defined Climate Action Plan, including key performance indicators (KPI) and documented results. National administrative authorities chosen by the Member States will oversee the monitoring of these new standards and may issue fines if they are not followed (European Commission, 2022a).

Many new demands will emerge in the shape of the "EU Sustainable Product Initiative" including:

- eco-design of products,
- embedded circular economy concepts
- energy and material efficiency of the products
- Life Cycle Assessment (LCA) of products (European Commission, 2022b)

Lastly, the Commission adopted a proposal for a new Carbon Border Adjustment Mechanism, which will be enforced in four years. It is applied to goods imported into the European Union that do not fulfill EU climate criteria and are high CO2 emitters. It is putting a carbon price on certain products to minimize "carbon leakage." This ensures that European emission reductions contribute to a worldwide decrease in emissions rather than moving carbon-intensive manufacturing outside of Europe. It also wants to inspire companies outside the EU to follow suit (European Commission, 2021). In addition, it is vital to note that carbon price has increased by more than 250 percent in the previous year, from 33 €/t in January 2021 to 88 €/t in February 2022 (Ampudia, Bua, Kapp, & Salakhova, 2022).

2.2 Consequences of Linear Economy and the need to transition

Using the linear economy model and not taking care of what happens at the end of the lifecycle of products, combined with years of environmentally harmful big-scale manufacturing and consumption helped to increase agricultural and product manufacturing, which stimulated the growth of the economy. However, it also contributed to the emergence and aggravation of several social, political, and environmental problems (Kumar, 2006).

- Environmental concerns

The reliance on fossil fuels as an energy input for many important industrial sectors globally is one of the fundamental characteristics of a linear economy. This includes the high dependence on natural resources, such as phosphorus to provide fertilizers for crops and other agricultural activities, as well as the significant overuse of fossil fuels to power production facilities, production of electricity, and a variety of other commodities. Scientists have demonstrated that the extraction and refining processes that use fossil fuels harm the environment, often resulting in irreversible damage to vulnerable ecosystems. (Sillanpää & Ncibi, 2017).

- Soil degradation and water contamination

Many nations, particularly China, where coal is the main major energy source, saw significant economic growth as a result of the global coal mining industry (Li & Leung, 2012). However, several studies have documented the negative effects of mining coal on the environment, particularly the contaminating effects of solubilizing and releasing nonorganic pollutants, such as toxic heavy metals, both during the extraction phase and when the waste rock is disposed of in landfills. Closely examined was acid mine drainage, which drastically changed the characteristics of exposed surface and ground waters (Komnitsas & Modis, 2006).

- Air pollution

Several harmful gases are polluting the air because of the mining of petroleum, its refining, the use of its numerous products, and the discarding of its associated pollutants. Through hazardous emissions and greenhouse gas emissions into the atmosphere, the transportation, agricultural, and petrochemical industries have a significant role in the global crisis in air quality. (Yang, Yuan, Chen, Yang, & Hung, 2017).

- Climate change

The biological balance of many marine ecosystems is in peril due to the melting of ice caps, increasing sea levels, and contaminated groundwater supplies in coastal aquifers, which might put at risk the lives of people who live along the coast, particularly on islands. The current economic model, which heavily relies on fossil fuels, unsustainable management practices, and highly polluting and waste-generating production procedures must therefore be replaced immediately (Konisky, Hughes, & Kaylor, 2016). Maintaining business as usual is no longer an option.

3 IMPLEMENTATION OF CIRCULAR ECONOMY

3.1 Definition of Circular Economy

The difficulty is that the circular economy is a comprehensive and multidimensional term, and how it is defined largely relies on who is doing the definition. Professionals involved in different industries will have distinct definitions of circular economy (CE) depending on what their area of research or work is. The reality is that laws, development plans, and policies will be created and then executed based on those definitions making defining CE crucial (Kalmykova, Sadagopan, & Rosado, 2018). Several definitions will be presented that have been proposed by various nonprofit organizations, scientists, and professionals that have focused their research studies and professional activities on the CE topic.

Certain practical definitions of CE were offered in some official EU documents, such as the one used in publications by the EU parliament, which states that CE is "a production and consumption model which involves reusing, repairing, refurbishing and recycling existing materials and products to keep materials within the economy wherever possible waste will itself become a resource, consequently minimizing the actual amount of waste. It is generally opposed to a traditional, linear economic model, which is based on a ‘take-make-consume-throw away’ pattern.” (European Parliamentary Research Service, 2018).

The Ellen MacArthur Foundation suggested the following definition in its paper "Toward the Circular Economy - Economic and Business Rationale for an Accelerated Transition": “an industrial system that is restorative or regenerative by intention and design. It replaces the end-of-life concept with restoration, shifts toward the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and business models” (Ellen MacArthur Foundation, 2013).

Some researchers with experience in manufacturing and industrial design described CE as “a regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling” (Geissdoerfer, Savaget, Bocken, & Hultink, 2017).

These definitions express similar concepts to describe the circular economy, like recycling, reuse, and remanufacturing of materials, lowering the demand for resources, recovering value from waste, the significance of circular economy as a means of achieving sustainable development, and its direct connection to social innovation.

Additionally, the circular economy needs to be defined in a way that mirrors the three dimensions of sustainable development (economy, environment, and society) as it is a vital enabler of sustainability. The present definitions often emphasize the economic aspect of things (how to generate growth from circularity while preserving the environment). The proposed definitions in this situation, which are sometimes marketed as a "conceptual framework of sustainable development," are very technical and ignore the other CE components. As some researchers have argued, in these definitions, the social component is hardly ever included (Sillanpää & Ncibi, 2019). The social aspect of CE is still seen as merely a byproduct of its implementation, despite being acknowledged in the terminology around it. Recently, a lot of scientists have been advocating to include this aspect of sustainability with the economic and environmental aspects in the CE definition (Murray, Skene, & Haynes, 2017).

If we look at the linear economy, resources are mined, and turned into goods, which are then utilized before being burned or dumped, resulting in a simple "production-consumption-disposal" structure. Therefore, it limits initiatives aimed at cutting down the end waste created by production and consumption. Contrarily, CE is rooted in a "production-consumption-recycling/recovering" framework that is responsive, sustainable, and more beneficial. In this structure, resources are recirculated so that the output of one is the input of another, maintaining the value of the products or their parts.

So regardless of what exact definition we take, in this context, the circular economy is anticipated to lay the groundwork for sustainable economic growth by introducing new business models, creating new job opportunities, conserving valuable resources (both finite and renewable ones), while preserving the environment and fostering social welfare. Many experts agree that securing a sustainable supply chain of raw materials, finished goods, energy, water, money, information, etc. is essential to achieving such awaited new goals. Implementing the circular economy concept in the whole supply chain through sustainable management strategies is considered to result in desirable results such as:

- Making the best use of resources (Rizos, Tuokko, & Behrens, 2017).
- Reducing material costs and pricing volatility.
- Using alternative supply chain setups to reduce energy usage and waste creation.
- Creating supply chain solutions that are more efficient by embracing new approaches to business and integrating both consumers and producers in the supply chain issues. (Bocken, Short, Rana, & Evans, 2014)
- Preventing waste creation at various phases can help reduce resource waste and the environmental problems associated with waste management.
- Increasing the amount of digitalization in the supply chain (Kalmykova et al., 2018)

To embrace the circular economy concept, businesses must include sustainable goals in their planning and be willing to collaborate with a growing network of partners and other third parties. One of the primary long-term goals is to prevent or reduce the environmental consequences of the intense activities and practices by industries, agriculture, mining, etc. by implementing closed-loop supply chains. As a result, such a strategy must address the whole product supply chain, with a particular emphasis on product recovery, reuse, and remanufacturing.

Closed loop supply chains are projected to confront two additional important problems throughout their implementation, namely forming alliances with opponents that you compete. Such a sensitive approach is required to overcome significant barriers to completing CE deployment. It is feasible to find common ground on which to gradually create trust among competitors. The actual difficulty, however, is to integrate ecological and social goals with the apparent economic ones. This is difficult since, in the recent past, particularly within the linear system, several partnerships between "alleged" competitors were formed for market domination and increased earnings, but at the price of the environment and/or social component. The other difficulty is determining how to deal with the inherent unpredictability in the business environment (changing resource prices, consumer needs, and transportation costs) and solving the corresponding problematic design of the supply chains. In this area, research efforts are focused on the creation of optimization models that use multiobjective stochastic programming (Tsoulfas & Pappis, 2006).

The concept of reverse logistics is heavily debated in the literature, with several definitions suggested. As a component of closed-loop supply chain management, including both forward and reverse supply chain management techniques it can be implemented in circular supply chains using a three-tiered model containing a manufacturer, distributor, and retailer. Key factors that influence reverse logistics strategic network design, as well as its value-added formation, usually involve collection platforms, accessible infrastructure, recovery methods the appropriate time to restore the product in the proper state it has to be to be recovered at the end of its expected lifetime, and for what new creations this product (or components of it) is being used or altered (Gaustad, Krystofik, Bustamante, & Badami, 2018).

Researchers have investigated different mitigation strategies that could potentially mitigate the supply chain risk and tried different approaches for different situations and various groups of risks. This thesis will explore how strategies that have a sustainable approach and contribute to environmental preservation are beneficial to risk mitigation.

3.2 Sustainable mitigation strategies

The conventional mining industry depends on a one-way stream of mineral resources: extracted resources, primary processed raw material, manufactured end-product, and post-use waste that needs to be discarded or wasted. By implementing a circular economic model that follows the flow of natural resources and products and by implementing highly effective and environmentally friendly technological innovations for the extraction and consumption of mineral resources, the mining sector can reinvent itself. Starting as material resources, then material products, and then flowing back as recycled material resources, it reflects a closed-loop flow of material. The 3Rs are used to execute the CE principle in the mining industry and mining-related activities: Reduce, Reuse, and Recover/Recycle (Sillanpää & Ncibi, 2019).

- Reduce

The collection of practices tries to lower the amount of energy and material needed to move resources that have been extracted along their entire supply chain. Therefore, "Reduce" refers to ensuring the efficient utilization of resources through digitalization, artificial intelligence, and optimized processes (Del Giudice, Chierici, Mazzucchelli, & Fiano, 2020) The reduce concept encourages the overall recovery of resources by decreasing mining dilution ratios and ore loss ratios, boosting recovery rates of mineral processing as well as smelting, developing technologies to deal with complex ore, decreasing emissions of major pollutants, such as tailings and mining wastewater. (Sillanpää & Ncibi, 2019).

- Reuse

It is the collective term for all established practices and methods for extending the useful lives of mining commodities and associated services (Watari, Nansai, & Nakajima, 2020). A typical example is reusing plastic grocery bags for domestic storage and reusing empty jars as drinking glasses. Lithium-ion batteries used in electric vehicles are an excellent example at the industrial level. If the battery loses 70-80% of its original capacity before or near the end of the life of an electric car, it may still be viable for stationary power storage applications such as grid storage or renewable energy storage. However, if the car dies before the battery capacity is used, the battery could be used in another vehicle (Richa, Babbitt, Gaustad, & Wang, 2014). Although reuse necessitates the highest quality at the end of life, it provides the secondary product with the greatest speed and with the least amount of energy, resources, and expense (Eckelman & Chertow, 2009).

- Recover/Recycle

If a product cannot be reused, it is a good practice to be recycled. Recycling intends to recover the mined minerals after usage and redirect such valuable resources back into the supply chain (González-Sánchez, Settembre-Blundo, Ferrari, & García-Muiña, 2020). Many key metals, such as aluminum, steel, and copper, are recycled. Due to the lengthy separation processes required to separate the elements of significance from goods that reached the end of their lifetime or are obsolete and incorporate them into new products, recycling has the lowest end-of-life product quality requirements but also has the slowest secondary product availability. It also contributes to the implementation of the circular economy concept as the most costly, resource, and energy-intensive activity (Allwood, Ashby, Gutowski, & Worrell, 2011).

3.2.1 Barriers to recycling critical and scarce metals

End-of-life product collection is a major undertaking, and the global actual recovery quantity of rare earth and critical metals is quite small in comparison to the present recycling potential. Li et al. (2022) outlined the barriers to recycling, considering the following aspects:

- Low levels of metal in finished goods

Due to their low percentage in end uses, the majority of materials are no longer recycled, which creates substantial challenges for their collection. Around 75% of the indium usage comes from liquid crystal displays, yet the level of indium in these displays individually is too low for common recycling techniques to be financially viable. The practical end-of-life recycling rate for gallium is less than 1% since it is applied with a low volume proportion in electronic equipment and is frequently further diluted and then lost in the overall recycling process.

- Specification of usage of materials

As technology develops, products become more diverse, which makes recycling more challenging. For instance, lithium-ion batteries (LIB) have complex designs and frequently undergo product type changes in reaction to new technological innovations. Different battery types and unconventional recycling methods stand in the way of increased recycling rates and more effective resource use.

- Production processes have become more complicated

As more combinations of materials with different characteristics are included in product designs to boost functionality, it becomes more challenging or impossible to separate or disassemble the components. For instance, LIBs are made up of over ten distinct parts, such as polymeric materials, binders, iron, copper, lithium, nickel, and manganese, each of which has peculiar traits that make recycling them difficult. It should be understood that the diversity and complexity of products will quickly increase the amount of metal loss if proper recovery is not achieved.

- Absence of product life cycle planning

When electronics reach their end of life, very few key metals are recycled, including neodymium, used in hard drives and headsets, and germanium, used in semiconductors. A major difficulty emerges from product life cycle design. Goods containing scarce metals are hardly ever designed to be reused at the end of life; as a result, products often do not display details or composition information that might be used to recognize the metal's presence, posing a significant obstacle to metal extraction during the recycling process. The design must be built on closed-loop recovery to maximize metal use efficiency from every recovery phase.

- Inadequate recovery technology and waste collection infrastructure

The primary cause of the absence of efficient metal recovery and separation technology is related to the fact that various metals necessitate different engineering approaches and current technology is unable to keep up with the complexity of modern goods. In many situations, many technologies have significant limits. Less than 1% of end-of-life items containing neodymium can be recycled since there is no reliable and financially feasible recycling technique. Therefore, it is essential to give priority to future research into effective metal separation techniques. There are several shortcomings in the present infrastructure and operations, including the absence of collecting and separating facilities, and sophisticated autonomous recycling systems, among others. If an efficient infrastructure for collecting the waste is not available, end-of-life items like cell phones and computers may be burned in municipal garbage landfills. Research into the recycling and use of discarded lithium-ion batteries in China's electronic devices indicated that, while respondents expressed an intention to recycle, the majority didn't have information on where to dispose of old lithium-ion batteries.

- Financial incentives

The major cause for the poor recycling rate of critical raw materials globally is poor recycling incentives, which manifests as high costs and a lack of economic appeal. For instance, there are significant obstacles to the actual recycling of lithium-ion batteries, namely the high cost. Although the Chinese authorities have supported the recycling of batteries, automobile dealers have not yet taken part in battery recycling because of economic barriers. Globally, 3% of used lithium-ion batteries are recycled for high-value metal recycling, with the vast majority being landfilled. Because of the extremely high cost, there is currently no extensive REE recovery in the world, and the actual recovery amount is very limited and hard to assess.

Thus, strengthening recycling management is essential, particularly through the implementation of relevant policy intervention strategies. An absence of economies of scale, asymmetric information, uncertainty in the supply, consumers' lack of knowledge about recycling metals from end-of-life products, and the idea that scrap treatment methods have not been standardized are some of many other barriers to recycling (Li et al., 2022).

Despite the challenges and barriers, each of these circularity solutions contributes to the reduction of material criticality problems. For instance, General Electric developed circularity-inspired solutions to address material criticality problems for rhenium, a critical material used in turbines. They proposed a "revert, recover, recycle, and reduce" strategy. Revert required only a minor change of its casting process, allowing casting waste to be reused in the master melt. Recover referred to a chemical technique designed to recover rhenium from grinding chips from turbine machining operations. Through recycling, they found ways to recover and clean components that were reused after in a master melt. Before implementing this approach, when they would replace an engine turbine blade assembly, the end-of-life blade assembly was discarded in a general scrap bin and sold to a recycler.

Following the rhenium price shock in 2007 (Konitzer, Duclos, & Rockstroh, 2012), General Electric evaluated its practices and created a process to clean the blades, and removes the extra coating on them, and with this process, it is possible to determine the exact alloys so they can be recycled and then used for the production of new blades avoiding usage of virgin rhenium, which also leads to lowering the costs of the whole manufacturing of blades (Gaustad et al., 2018).

3.2.2 Urban Mining (UM)

Urban and landfill mining operations are shown and addressed to highlight their significance in establishing circular practices in the mining industry like recovery and recycling strategies that offer possibilities to recover metals and mineral resources from waste. Urban mining, broadly speaking, refers to all the actions and processes intended to recover materials, composites, and energy from goods, buildings, and waste produced by "urban catabolism". Urban areas are therefore viewed as sources of anthropogenic resources that may be utilized repeatedly, recycled, and reused.

China is one of the world's top providers and users of both resources and energy. Urban mining was first conceptualized in China in the early twenty-first century, mostly as a result of domestic research efforts. The Chinese authorities approved the idea and launched the Urban Mining Demonstration Base Construction (UMDBC) program in 2010 following the scientific "promotion" of the proposal, which detailed the economic and environmental benefits of UM. China is attempting to build a new approach to the utilization of resources and commodities through this UM-based initiative to:

- Mitigate the severe impact of energy shortages and resource scarcity, especially given how heavily the nation depends on natural resources for economic growth.
- Assist in lowering environmental pollution caused by the extraction, processing, and disposal of resources.
- Ensure a reduction in carbon emissions.

According to reports, the UMDBC Program may cut energy consumption by 35 million tons of standard coal, wastewater discharge by 2.2 billion tons, sulfur dioxide emissions by 0.78 million tons, and carbon dioxide emissions by 80 million tons when compared to the usage of raw natural materials. Such circular activities will facilitate and expedite the transition to sustainable communities, which will in turn encourage the growth of numerous new mining and processing industries and create new opportunities in these fields (Hu & Poustie, 2018).

3.2.3 Landfill mining (LFM)

Along with the widely used method of extracting biogas from landfills (more particularly, methane), which is known as landfill mining, there is also the possibility of extracting material resources from ancient landfills. LFM is a "method for retrieving materials or other solid natural resources from waste items that have previously been disposed of by burying them in the ground " according to Krook, Svensson, & Eklund (2012). LFM was once seen as a way to address urgent problems with solid waste management, such as the scarcity of landfill space and the dangers posed by local pollution.

With the adoption of the CE concept, landfill mining has evolved into an environmentally friendly strategy that can successfully address the problem of waste on a global scale through a series of activities, such as the treatment and extraction of the materials, recycling of materials found in the landfills along with power generation procedures. Numerous scholars have lately proposed the idea of improved landfill mining as a more holistic approach than a traditional one. The goal of this approach is to recover as much energy and resources as possible while still maintaining ecological and social standards. It requires thoroughly processing the various waste streams utilizing cutting-edge technology. In this context, Kieckhäfer, Breitenstein, & Spengler (2017) conducted an economic analysis of landfill mining operations based on material flow and examined several relevant scenarios.

Implementing an LFM approach should have the following objectives:

- Focusing on the removal of landfilled waste to lower its space/volume for lifespan extension, particularly given that the amounts of the created waste will continue to rise.
- Eliminating pollution sources, thus conserving the environment and enhancing public health. - reclaiming resources, both material, and energy.
- Carrying out well-thought-out rearrangement and cleaning up before the waste is landfilled once more. In light of the current problems with solid waste management (economic losses and environmental issues), as well as the fact that waste generation rates are increasing globally, the deployment of the LFM plan and the implementation of related processes and procedures are highly relevant to a global scale.

The World Bank estimates that over two billion tons of solid waste were produced globally in cities in 2016. The yearly waste creation is predicted to rise from 2016 levels to 3.40 billion tons in 2050 for several factors, including the fast population expansion and urbanization (World Bank, 2022). Having established that, we must take into account the fact that the majority of landfills are composed of 50–60% soil-type material, 20–30% combustibles (such as plastic, paper, and wood), and 10% inorganics (such as concrete, stones, and glass), as well as a very small percentage of primarily ferrous metals. Therefore, any goal for recovering materials from landfills should be feasible and have a clear priority approach. In reality, the importance of recovering this or that resource from landfills will "adjust" based on economic factors (particularly those connected to the cost of retrieving and further processing landfilled materials) and market demand (Watson & Powrie, 2013).

4 RESEARCH METHODOLOGY

4.1 Smart Meters

Smart meter technology is perceived as a key enabler of the energy transition, as well as a driver of digitalization and energy efficiency. There is a difference between standard and smart metering equipment. Standard metering devices are digital meters that allow the client to read consumption data. Smart meters also include a communication module, known as a smart meter gateway, which can be used for purposes other than monitoring, like taking over control functions. For instance, concepts like variable tariffs, which means that the unit rates and standing charge can increase or decrease if the cost of wholesale energy changes, and load shifting, which allows moving electricity consumption from one time period to another, can be utilized if smart meters are implemented. End-user self-scheduling via a home energy management system (HEMS) can be used to capitalize on consumers' flexibility (Knayer & Kryvinska, 2022). Moreover, by comparing the measured data to actual values, it is possible to determine if the power grid is operating at its best and if the amount of power stored in reserve (measured in kilowatts) inside the grid can be optimized. Electricity costs are directly impacted by changes in the amount of power stored in reserves. Additionally, the data from the smart meters can be used when designing the size of generation plants (hydro plants, photovoltaic plants, etc.) and storage, to avoid the problems of missing data when planning big projects like these.

To be able to have the technology that enables the benefits mentioned above, electronic components made of metals are needed. An electricity smart meter is made up of 79 % electronic components, 12 % polymer, and 9 % metallic parts. (Markizeti & Heringer, 2021). Therefore, in the scope of this thesis, an analysis of the risk of the materials that compose the electronic components of the smart meters was done, and how those risks could be mitigated using sustainability strategies was explored. Two smart meters are taken into account, a single-phase meter from the AM550 series, and a three-phase meter IE.5. The latter is a next-generation meter, which is why it is important to evaluate the risks that could be a cause for disruption in the future.

The IE.5 series metering devices have diverse applications in power generation, transmission, distribution, and consumption. The Energy IoT (eIoT) modular platform serves as a basis for the next generation of electricity meters and is suited for smart grids, it supports all existing Energy IoT solutions in the smart digital grid environment and the creation of smart cities with an emphasis on sustainability. Products built on the eIoT modular allow monitoring and maintaining the hardware's functionality and metrology while also providing a platform for applications that integrate the products into a larger energy IoT system. It also provides insights into network control, fault detection management, better energy efficiency, higher data security, forecasting energy consumption trends, lower operating costs, and the potential for organic and technological growth of electricity distribution (Iskraemeco, 2021).

4.2 Definition of data

One of the goals of this thesis was to map and identify the potential risks and disruptions that could affect the supply chain of smart meters and investigate how sustainability measures can help mitigate those risks.

The focus was put on the analysis of the first step in the upstream supply chain, meaning the extraction and processing of raw materials (metals and minerals) that provide critical functionality to electronic products, among which is the smart meter. By literature review, groups of risks were established, and for each group accordingly, metrics were defined that could help measure and quantify the risks.
Based on research demonstrating how abrupt changes in demand may have an upward spiraling effect on the supply chain, the indicators linked to demand risks were chosen based on their capacity to capture the market pull for a particular commodity (Buchholz & Brandenburg, 2018)

4.2.1 Demand risk metrics

Supply risks are concerned with a material's capacity to be physically obtained from accessible resources as well as its physical availability concerning those resources. The research has demonstrated that variables that affect supply risk include global reserve, ore concentration, index of depletion, byproduct extraction, and end-of-life recycling input rate (Althaf & Babbitt, 2021; Redlinger & Eggert, 2016; Blengini et al., 2020).

- Annual mining production is a measure of a material’s total worldwide production to satisfy demand across all industries. Literature has made use of annual production data to forecast bottlenecks in material supply and demand.

- Consumption by the electronics industry is the proportion of all yearly material production utilized in electronic technologies in the European Union. Moreover, all electronics are included in the source data, including consumer electronics, embedded electronics (such as electric car motors), and electric appliances, according to the Statistical Classification of Economic Activities in the European Community, referred to as NACE, which is the industry standard classification system used in the EU.

- Price signalizes the level of market demand for a resource that can be in short supply. Data are provided as US dollars per kilogram of material and refer to 2021.
- Price volatility was calculated as a 5-year coefficient of variance in a material's yearly average pricing.

4.2.2 Supply risk metrics

The unequal geographic distribution of metal resources results in production systems that are dispersed unevenly throughout a small number of nations. Even though a resource is physically available, geographic concentration may make it difficult to obtain it. This is often the case owing to political or socioeconomic factors in the region that produces the resource or in regions that depend heavily on imports. On geopolitical risks, several metrics have been released (Griffin, Gaustad, & Badami, 2019; Gemechu, Helbig, Sonnemann, Thorenz, & Tuma, 2016; World Bank, n.d.).

- The global reserve is the stock of economically extractable mineral commodities.

- Ore concentration is calculated as the mass proportion of material contained in its usual ore deposits is known as. Lower concentrations represent scarcer, more dispersed commodities that are more expensive or take more energy to extract.

- The static index of depletion of a commodity is the ratio of global reserves to yearly output (metric tons/year), and it indicates the number of years the resource will last assuming consumption keeps at its current pace. As new material reserves are found and as yearly output or demand of materials rises or falls, the index of depletion may alter. However, the metric provides a hint about the supply risk in the short term caused by geological scarcity combined with known demands.

- Byproduct production percentage measures how much a commodity is extracted as a byproduct of procedures used to extract another metal and how it lacks its production infrastructure. The capacity to quickly scale up production of a byproduct may be constrained since mining infrastructure is predominantly linked to a small number of commercially viable metal ores that are geographically concentrated unless the "parent" metal experiences a comparable demand signal.

- End-of-Life Recycling Rate of Input (EOL – RIR) is the ratio of the EU's raw material supply to old scrap recycled in the EU. In other words, it refers to the creation of secondary materials from post-consumer functional recycling (old waste) that are used to process and manufacture products instead of raw materials.

4.2.3 Socio-Political risk metrics

Processes for extracting materials may have major environmental effects related to energy usage, contaminant emission, and waste creation. However, given both threatening environmental conditions and rising public scrutiny of supply chain accountability, these metrics do represent the long-term viability of mining activities, even if they may not pose an immediate threat to the availability of materials. That they include both the immediate effects of material extraction and all the upstream consequences related to creating energy, chemicals, infrastructure, and other inputs to those extraction processes. The criteria used are based on life cycle impact assessment techniques that are often used to evaluate the environmental impact of materials (Nuss & Eckelman, 2014).

- Geographical concentration of production (HHI) measures how much material is produced in a limited number of countries. If a country restricts or cannot sustain supply, as in the case of particular trade laws, political potential barriers, or abrupt disruptions, supply risks may increase. The Herfindahl-Hirschman Index (HHI), a statistical indicator of market concentration (Eurostat, n.d.), was used to quantify geographical production concentration, calculated using (1):

$$HHI = \sum_{i=1}^{N} \left(\frac{X_i}{X}\right)^2 \tag{1}$$

  Where N is the number of countries of production for the materials, X_i is the quantity of a material produced by each country and X is the total world production of that material.

- Net import dependency is the percentage of the EU's consumption that is met by imports as opposed to domestic production. This indicator, which accounts for the possible dangers associated with an area's reliance on imports and potential inability to access those supplies under certain conditions, was specifically evaluated from the perspective of the European Union.

- Socio-political weighted geographic concentration (PSAV-HHI) represents the likelihood of political unrest or obstructive social circumstances in nations with concentrated material production. Such unpredictability might result in vulnerabilities in the supply chain that could affect the health and safety of workers in the mining and processing of raw materials. The previously derived HHI measure is given a socio-political weighting in this metric. The World Bank reports six total Worldwide Governance Indicators (WGI), and the weighting is based on the Political Stability and Absence of Violence (PSAV) indicator, which has been demonstrated in the past to predict social supply chain vulnerabilities. A dimensionless measure, the PSAV index ranges from bad (-2.5) to good (+2.5). The PSAV index is multiplied by the HHI index and gives this metric.

- Using a social life cycle assessment of workers' rights, welfare, governance, infrastructure, and civil rights in the country of material production, the social hotspots score indicates the social risks of material production. These elements may also bring indirect risks to businesses that are becoming more conscious of public opinion and uproar when human rights breaches are discovered.

4.2.4 Environmental risk metrics

- Global warming potential assesses the greenhouse gas effect along the supply chain, including emissions that occur during material extraction (such as when fuels are used for transportation and energy) and upstream energy activities.

- Cumulative energy demand refers to the main energy flows that participate in extracting materials, including both direct energy inputs and the upstream primary energy required to produce energy carriers.

- Freshwater eutrophication refers to the quantification of the potential for eutrophication of freshwater ecosystems caused by the release of metals and other pollutants during mining operations or upstream activities. Freshwater eutrophication is the term used to describe the excessive growth of aquatic plants or algal blooms caused by high nutrient levels in freshwater ecosystems like lakes, reservoirs, and rivers. This can result in unpleasant tastes and odors in drinking water, fish deaths due to oxygen depletion, etc.

- Human Toxicity (Cancer and Non-Cancer) measures the impacts of the release of metals and other pollutants during mining operations or upstream activities on the negative health effects on human beings brought on by the intake of toxic substances through inhalation of air, food, or water ingestion, penetration through the skin, whether related or not to cancer.

- Terrestrial Acidification is measured as the decrease of pH value of rain and fog, which has the impact of harming ecosystems by increasing the solubility of metals in soils and removing nutrients from soils, among other things. It is expressed in the mass of sulfur dioxide equivalents, caused by the release of metals and other pollutants during mining operations or upstream activities. Fossil fuel burning, which releases sulfur dioxide and nitrogen oxide that combine with condensed water in the atmosphere to form rain, is the primary process driving the effects of acidification

4.3 Implementation of the data and mapping of the risks

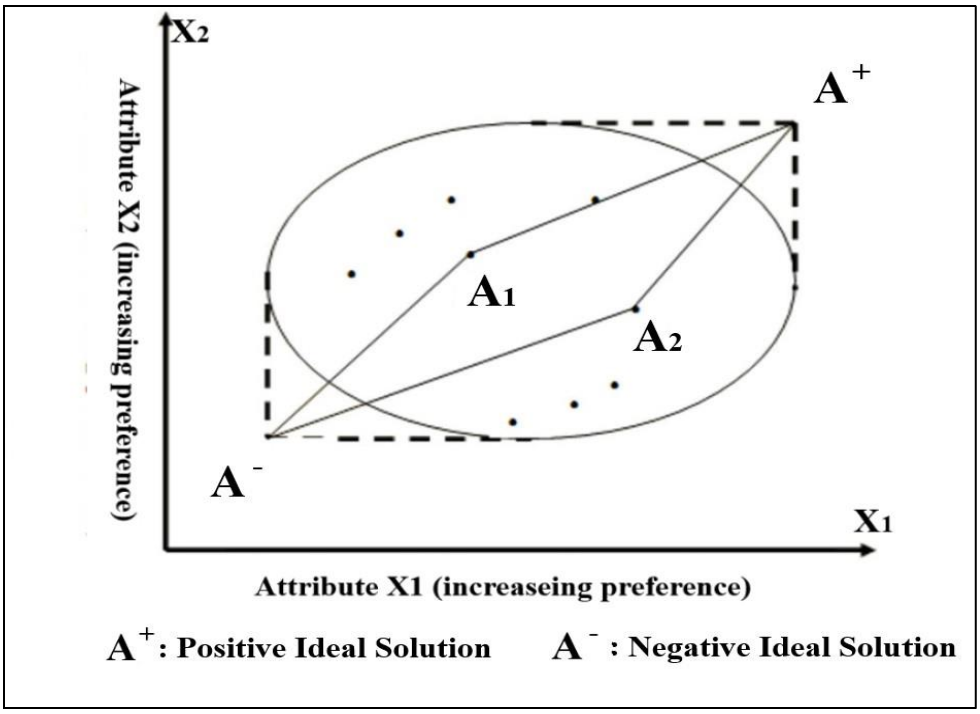
While reviewing the literature, the potential method that was taken into consideration to be used for mapping the risks was the Bayesian network methodology, because it allows the use of qualitative and quantitative data about relations among risk events (Lockamy, 2019). This method is suitable for mapping the probability of a certain risk and how one parameter or event can affect another. For decision-making or choosing what the best mitigation strategy is, Grey Relational Analysis was researched (Rajesh, Ravi, & Venkata Rao, 2015). Several others were investigated such as the Probability-impact matrix (Qazi & Akhtar, 2020) and Fault Tree Analysis (Ruijters & Stoelinga, 2015).

Other papers were reviewed where multi-criteria decision analysis (MCDA) was used. The most frequent use of MCDA is to resolve multiple conflicting objectives. Figueira, Greco, & Ehrogott (2006) present an overview of the existing methodologies that may be utilized for MCDA. The main distinction between MCDA methodologies is the application of compensatory and non-compensatory approaches. While non-compensatory techniques often rely on outranking principles that involve pairwise evaluation of alternatives, compensatory approaches generally permit trade-offs between the indicators.

These recommendations and analyses of comparable situations have led to the conclusion that the TOPSIS (Technique for Order by Similarity to Ideal Solution) method is most appropriate for the issue at hand in this thesis. TOPSIS was also chosen because it is among the most commonly utilized methods, it is simple to use and implement, it resembles human thinking, and it has been shown to have the lowest rank reversal (change in ranks by adding/deleting alternates) among comparable methods. TOPSIS was originally developed by Ching-Lai Hwang and Yoon in 1981 with further developments by Yoon in 1987, and Hwang, Lai, and Liu in 1993 (Kumar, Jagadish, & Ray, 2014).

The TOPSIS method uses Euclidian distance measure for identifying the alternative between the Positive Ideal Solution (PIS) and Negative Ideal Solution (NIS). PIS is a hypothetical alternative created utilizing the indication with the best score when it comes to benefits and the indicator with the lowest score when it comes to costs or negative consequences. Similar to PIS, NIS is a speculative alternative that was developed using the opposite rationale, as shown in Figure 3. The option with the greatest score in TOPSIS is the one that is further away from the NIS and closer to the PIS (i.e., mimics PIS characteristics) (calculated using Euclidian distance measure).

Figure 3. The basic concept of the TOPSIS method



Adapted from Balioti, Tzimopoulos, & Evangelides (2018, p. 2).

To correctly structure the decision-making problem, Kalbar, Karmakar, & Asolekar (2012) developed a scenario-based decision-making strategy. In MCDA, indicator weights have a substantial impact on the final rankings of the alternative. The rankings that may be derived for each scenario, which more accurately represent the stakeholders' preferences, summarize the stakeholder viewpoints in terms of weights. Six scenarios depicting the changing weights of each type of indicator expressing the preferences of various stakeholders were established in light of this and presented below.

The solution steps are as follows:

1. The matrix x_{ij} represents the endpoint of the i^{th} material and the j^{th} metric. Each value of x_{ij} is normalized using Equation 2 to generate a normalized endpoint matrix r_{ij}.

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \tag{2}$$

2. The weighted decision matrix is determined by the normalized matrix multiplied by the weighting factor w_j for each metric depending on the scenario, to obtain a weighted normalized endpoint matrix v_{ij},

$$v_{ij} = w_i r_{ij,(i=1,..,m;j=1,...,n)} \tag{3}$$

3. The ideal positive solution is composed of the value of every attribute from the weighted matrix and calculated using Equation 4, and the negative ideal solution is composed of the worst value of every attribute from the weighted matrix using Equation 5.

$$PIS, v_{ij}^{+} = \{(\,{}_{i}^{max} v_{ij} \mid j \in J1), (\,{}_{i}^{min} v_{ij} \mid j \in J2) \mid i = 1, \ldots\ldots, m\} \quad (4)$$

$$NIS, v_{ij}^{-} = \{(\,{}_{i}^{min} v_{ij} \mid j \in J1), (\,{}_{i}^{max} v_{ij} \mid j \in J2) \mid i = 1, \ldots\ldots, m\} \quad (5)$$

In (4) and (5), m is the total number of materials (m = 48). J1 is the set of metrics for which the highest value is the best value i.e. ideal best, as in the case of ‘Global Reserves’ for which a higher number of reserves represents the best case. J2 is the set of metrics for which the lowest value is the best outcome, i.e. ideal worst, as in the case of ‘Global Warming Potential’. The total number of metrics considered in this analysis is (n = 18).

4. The distance of every feasible solution from the ideal solution and the negative ideal solution is calculated respectively by Equation 6 and Equation 7.

$$S_i^{+} = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^{+})^2, (i = 1, \ldots, m; j = 1, \ldots, n)} \quad (6)$$

$$S_i^{-} = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^{-})^2, (i = 1, \ldots, m; j = 1, \ldots, n)} \quad (7)$$

5. Calculation of the relative degree of approximation is determined by (8).

$$FS_i = \frac{S_i^{-}}{(S_i^{+} + S_i^{-})} \quad (8)$$

The evaluation object is ranked according to the value of the relative degree of approximation. The bigger the value is, the better the evaluation object is.

- Scenarios and weightings

Once the data was gathered, six scenarios were defined. The scenarios depict various risks that might be brought on by sudden occurrences like the inability of supply to keep up with rising electronic product demand, sudden demand causing price volatility, social risks to workers in the resource extraction industry, geopolitical barriers to obtaining material resources and environmental effects because of weak regulatory requirements.

To evaluate the risks under various circumstances, a baseline scenario is first established, with all criteria given equal weight (5.56 %). When a supply chain for materials is suddenly disrupted, both supply and demand are immediately affected, because of abrupt changes to mining, processing, and manufacturing operations (Dente & Hashimoto, 2020), which leads to the second scenario, where 80% was distributed equally (16%) to metrics that capture the physical availability of products. A consequence of such disruptions is a mismatch in demand and supply and could have an influence on the economy in the form of price increases and volatility, which in turn may generate unexpected events both up and down the supply chain (Leader, Gaustad, & Babbitt, 2019). Therefore in the third scenario, 80% was distributed equally (20%) to metrics that relate to material demand. The physical availability of a material and whether it is obtained through primary mining or as a by-product from other metal ores determine whether it can be produced and supplied at a larger scale to meet an increase in demand (Graedel, Harper, Nassar, & Reck, 2015). In the fourth scenario, 80% was distributed equally (20%) to metrics that represent social risks. Geopolitical factors may exacerbate these immediate effects of sudden disruptions in supply and demand if material sourcing is dependent on a small number of countries in addition to border shutdowns or labor disruptions, such as those related to attempts to slow the COVID-19 transmission (Guan et al., 2020). In the fifth scenario, 40% was distributed equally (20%) to metrics related to geopolitical and trade risks. Material extraction activities are further characterized by the tendency for major environmental impacts due to energy use, pollutant emission, and waste generation. These consequences may not pose immediate threats to material availability, but they do reflect mining activities' long-term sustainability, both threatening environmental conditions and soaring public criticism of supply chain responsibility (Nuss & Eckelman, 2014). Finally, in the sixth scenario, 80% was distributed equally (16%) to metrics that capture the environmental risks. The definition of each scenario and how the weighting was distributed is shown in Table 2. In Table 3 all weights are presented for each metric and group of risks.

Table 2. Scenario description and corresponding metric weightings

Scenario Description	Metric Weightings
1. BASELINE: Supply, demand, sociopolitical and environmental factors pose equal risks	Equal weighting was assigned to all 18 metrics (5.56%)
2. SUPPLY CAN NOT MEET INCREASED DEMAND: Some event causes an increased demand for electronics and decreased production of needed materials due to the closure of mining sites and metal processing units or increased production of green energy technology.	Higher weighting (16%) was assigned to metrics that capture the physical availability of products: Global Reserves, Ore Concentration, Static Index of Depletion, Production% as Byproduct, and End-of-Life Recycling Input Rate. Electronics Sector Consumption weighted 12%; the remaining 8% is spread across all other metrics.
3. ECONOMIC VOLATILITY IS CAUSED BY DEMAND INSTABILITY: Events lead to economic downturns followed by material surges as economies try to recover and function as before, causing price hikes.	Higher weighting (20%) was assigned to metrics that relate to material demand: Price, Price Volatility, and Electronic Sector Consumption. The remaining 40% is distributed across all other metrics.
4. GOVERNMENTS ABILITY TO OVERREACH: Government overreach fuels internal strife in nations with weak governance and unstable political systems, increasing the danger to society—particularly from forced labor, layoffs, poor working conditions, and worker disease.	Higher weighting (20%) was assigned to metrics that represent social risks: Sociopolitical weighted HHI and Social Hotspots. Electronics Sector Consumption weighted 15%; the remaining 45% is spread across all other metrics.
5. GEOPOLITICAL TENSIONS: Border closures, war, and trade tariffs affect the flow of metals and related trade relations between countries' economies.	Higher weighting (20%) was assigned to Geographic Production Concentration and Import Reliance (EU perspective) metrics. Electronics Sector Consumption weighted 15%; the remaining 45% is spread across all other metrics.
6. ENVIRONMENTAL CONCERNS TAKE LOWER PRIORITY DURING OTHER DISRUPTIVE EVENTS: Environmental rules become less important when nations struggle to maintain their economy, escalating environmental dangers associated with material production.	Higher weighting (16%) was assigned to metrics that represent environmental risks: supply chain Global Warming Potential, Cumulative Energy Demand, Freshwater Eutrophication, Human Toxicity, and Terrestial Acidification. Electronics sector consumption weighted 12%; the remaining 8% is spread across all other metrics.

Adapted from Althaf & Babbitt (2021).

Table 3. Weightings for each metric and group of risks in %

Scenario	Supply					Demand			
	GR (%)	OC (%)	SID (%)	BYP (%)	EOL-RIR (%)	AMP (%)	ESC (%)	P (%)	PV (%)
Baseline	5.56	5.56	5.56	5.56	5.56	5.56	5.56	5.56	5.56
1	**16**	**16**	**16**	**16**	**16**	0.67	**12**	0.67	0.67
2	2.67	2.67	2.67	2.67	2.67	2.67	**20**	**20**	**20**
3	3	3	3	3	3	3	**15**	3	3
4	3	3	3	3	3	3	**15**	3	3
5	0.67	0.67	0.67	0.67	0.67	0.67	**12**	0.67	0.67
Scenario	**Socio-political**				**Environmental**				
	HHI (%)	SP HHI (%)	SH (%)	IR (%)	GWP (%)	CED (%)	FE (%)	HT (%)	TA (%)
Baseline	5.56	5.56	5.56	5.56	5.56	5.56	5.56	5.56	5.56
1	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67
2	2.67	2.67	2.67	2.67	2.67	2.67	2.67	2.67	2.67
3	3	**20**	**20**	3	3	3	3	3	3
4	**20**	3	3	**20**	3	3	3	3	3
5	0.67	0.67	0.67	0.67	**16**	**16**	**16**	**16**	**16**

Adapted from Althaf & Babbitt (2021).

4.4 Collection of data

In total, forty-eight materials were analyzed. The materials taken into consideration are the most used metals and minerals in electronic products, and also that match the materials analyzed in the FlonIskra internal report, for Iskraemeco's smart meter (Markizeti & Heringer, 2021). Divided into groups of Base metals, Precious metals, Critical Raw Materials, Rare Earth Elements (REE), Hazardous Metals, and Others, as shown in Table 4.

Some Critical Raw Materials are excluded because of a lack of data. In total 14 - fluorspar, strontium, coking coal, borates, bauxite, natural rubber, and heavy REE - holmium, erbium, thulium, ytterbium, lutetium, scandium. Some have an important role in the production of electronic components or are a part of the processing of other materials like fluorspar, which is a key ingredient in the processing of aluminum and uranium, and strontium which is used for electrolytic production of zinc (U.S. Geological Survey, 2022). Great potential exists for use of scandium even though at the moment it is used for research purposes, because of its low density as aluminum and much higher melting point (Royal Society of Chemistry, n.d.-b). Erbium is used in the making of fiber optic cables and laser repeaters. Although borates were used in more than 300 applications, more than three-quarters of world consumption was used in ceramics, detergents, fertilizers, and glass, so the majority of applications are not related to the manufacturing of electronic components (U.S. Geological Survey, 2022). Holmium can absorb neutrons, so it is used in nuclear reactors to keep a chain reaction under control and its alloys are used in some magnets, so it plays an important role as a material needed for green energy transition (Royal Society of Chemistry, n.d.-a). In the case of Hazardous Metals, Mercury was excluded because of a general absence of use.

The latest available data was collected from different sources, such as Mineral Commodity Summaries by the United States Geological Survey (USGS), a report on the EU's list of Critical Raw Materials 2020, and previous journal articles that researched similar topics like Nuss & Eckelman (2014), Nassar, Graedel, & Harper (2015) and Sverdrup, Ragnarsdottir, & Koca (2017). For some materials data was not available and if it was suitable proxy values were used. In the end, for three materials – sulfur, silicon, and phosphorus, data was not available for the group of metrics concerning Environmental risk. They are extracted through the Ecoinvent Simapro database (https://simapro.com/) by implementing LCA methods (Althaf & Babbitt, 2021) and a license is needed to get access, so for those materials, qualitative analysis will be done in the discussion part of the thesis. A detailed overview of each metric and material will be presented in the following paragraphs.

Table 4. List of analyzed materials and their symbols by groups

Group of Materials	Material	Symbol	Group of Materials	Material	Symbol
Base Metals	Aluminum	Al	**Critical Raw Materials**	Niobium	Nb
	Copper	Cu		Phosphorus	P
	Iron	Fe		Silicon	Si
	Magnesium	Mg		Tantalum	Ta
	Nickel	Ni		Tellurium	Te
	Titanium	Ti		Tin	Sn
	Zinc	Zn		Tungsten	W
Precious Metals	Gold	Au		Vanadium	V
	Palladium	Pd	**REEs**	Cerium	Ce
	Platinum	Pt		Dysprosium	Dy
	Rhodium	Rh		Europium	Eu
	Silver	Ag		Gadolinium	Gd
Critical Raw Materials	Antimony	Sb		Lanthanum	La
	Barite	Ba		Neodymium	Nd
	Beryllium	Be		Praseodymium	Pr
	Bismuth	Bi		Samarium	Sm
	Cobalt	Co		Terbium	Tb
	Gallium	Ga		Yttrium	Y
	Germanium	Ge	**Hazardous Metals**	Cadmium	Cd
	Graphite	Gr		Chromium	Cr
	Hafnium	Hf		Lead	Pb
	Indium	In	**Others**	Arsenic	As
	Lithium	Li		Molybdenum	Mo
	Manganese	Mn		Sulfur	S

Source: Own work.

4.4.1 Demand risk metrics

The main data source used for annual production and price, for most materials, is the Mineral Commodity Summaries by the United States Geological Survey (USGS) (U.S. Geological Survey, 2022). In the case of REEs, annual production data for individual REES was estimated by proportionally allocating the annual production from the total for REE from USGS 2022. Percentages for each REE were taken as a share of the total annual production from Althaf and Babbitt (2021).
The data for electronic sector consumption was taken from the report Study on the EU's list of Critical Raw Materials 2020 (Blengini et al., 2020). NACE codes used were C24 - Manufacture of basic metals; C25 - Manufacture of fabricated metal products, except machinery and equipment (when related to alloys, wires, screws, generators); C26 - Manufacture of computer, electronic and optical products; C27 - Manufacture of electrical equipment; C29 - Manufacture of motor vehicles, trailers, and semi-trailers; C30 - Manufacture of other transport equipment; C33 - Repair and installation of machinery and equipment (European Commission, n.d.).

The price volatility coefficient was calculated with the following steps for a 5-year period:

1. Finding the mean of the data set.
2. Calculating the difference between each data value and the mean.
3. Squaring the deviations for the elimination of negative values.
4. Adding the squared deviations together.
5. Dividing the sum of the squared deviations by the number of data values (Hayes, 2022).

The assumptions and proxies used in data collection are detailed below:

Annual production: titanium production data represents titanium metal production and iron represents raw steel production. REE production data refers to REE oxide production. Platinum production data is used as a proxy for rhodium, as rhodium is mostly produced as a byproduct of platinum. Barite is used as a proxy for barium in all metrics.

Price: Price data is the annual average price per kilogram of materials in the year 2022. REE price represents REE oxide price with a certain minimum REE content. Titanium price represents titanium metal price. Gallium price is the price of high-purity refined gallium imports. Graphite flake import price is used for graphite. Tantalum price is dollars per kilogram of tantalite Ta_2O_5 content and the price of vanadium is a dollar per kg of vanadium pentoxide as reported by USGS. For praseodymium, samarium, and gadolinium is used oxide price as reported by Statista - praseodymium(Statista, n.d.-a) and samarium (Statista, n.d.-c) for 2020, gadolinium for 2021 (Statista, n.d.-b).

4.4.2 Supply risk metrics

The main data source used for global reserves is the Mineral Commodity Summaries by the United States Geological Survey (U.S. Geological Survey, 2022) for most materials. Global reserves for individual REEs were estimated based on total REO (Rare Earth Oxide) global reserve data reported by USGS 2022 and the content (%) of each REE in its REO ore reported by Althaf & Babbitt (2021). Data on production % as a byproduct for all materials are taken from Nassar, Graedel, & Harper (2015) while ore concentration is taken mostly from (Sverdrup, Ragnarsdottir, & Koca (2017), and data for several materials individually from different studies was taken. For EOL - RIR (%) data was taken from Blengini et al. (2020).

The assumptions and proxies used in data collection are detailed below:

Global reserves: Due to the lack of availability of disaggregated data for Platinum Group of Metals (PGMs), available aggregated data for PGMs are reported for all PGMs considered. For aluminum, bauxite reserve is used as a proxy, for iron, iron content in ore reserve is used, for titanium, mineral concentrate reserve is used, in the case of magnesium, magnesium compound reserve data is used. In the case of gallium, the reserve is calculated based on the recoverable content of gallium in bauxite, as USGS estimates that the world resource of gallium in bauxite is one million tons where only 10% is recoverable. Due to lack of data availability in USGS, data for indium is calculated according to the reports from USGS that the indium content of zinc deposits from which it is recovered ranges from less than 1 part per million to 100 parts per million. Data for cadmium is calculated according to the reports from USGS that the cadmium content of typical zinc ores averages about 0.03%. Bismuth world reserves are usually estimated based on the bismuth content of lead resources because bismuth production is most often a byproduct of processing lead ores. For silicon qualitative estimates are not available, more than 90% of the Earth’s crust is composed of silicate minerals, making it the second most abundant element, so as a proxy it is taken the maximum number of reserves among the analyzed materials. For germanium data was taken from Frenzel, Ketris, & Gutzmer (2014).

Ore concentration: Due to the lack of availability of disaggregated data PGMs, available aggregated data are reported for all PGMs considered. For ore concentration, the highest % in the data range by Sverdrup et al. (2017) was used. Data reported in g/t was converted to a percentage. For bismuth data was taken from Krenev, Drobot, & Fomichev (2015). For sulfur data was taken from Haldar (2020). For phosphorus data was taken from Barker (2019). For arsenic data was taken from Long, Peng, & Bradshaw (2012).

Static Index of depletion: For magnesium, the index of depletion is calculated as the ratio of magnesium compound reserve to magnesium metal production and for iron, the depletion index is calculated as the ratio of steel production to iron crude ore reserve.
Production % as a by-product: For all the materials, data is adopted from Nassar et al. (2015). The reported data in this study should be assumed as a maximum case, since when a material's production percentage was reported to be < x% (less than x %), the metric was parametrized to be x%.

4.4.3 Socio-political risk metrics

All the socio-political metrics except net import reliance were estimated based on the geographical production distribution of materials in the year 2022 as reported by USGS. Net import reliance data is collected from Blengini et al. (2020).
HHI, PSAV-HHI: Due to the lack of availability of disaggregated data for each REE and PGMs, available aggregated data for REE and PGM production distribution are used to estimate these metrics for all REEs and PGMs analyzed.
Data for Social Hotspots was taken from Althaf & Babbitt (2021) for each country and calculated using the same method as for HHI.

4.4.4 Environmental risk metrics

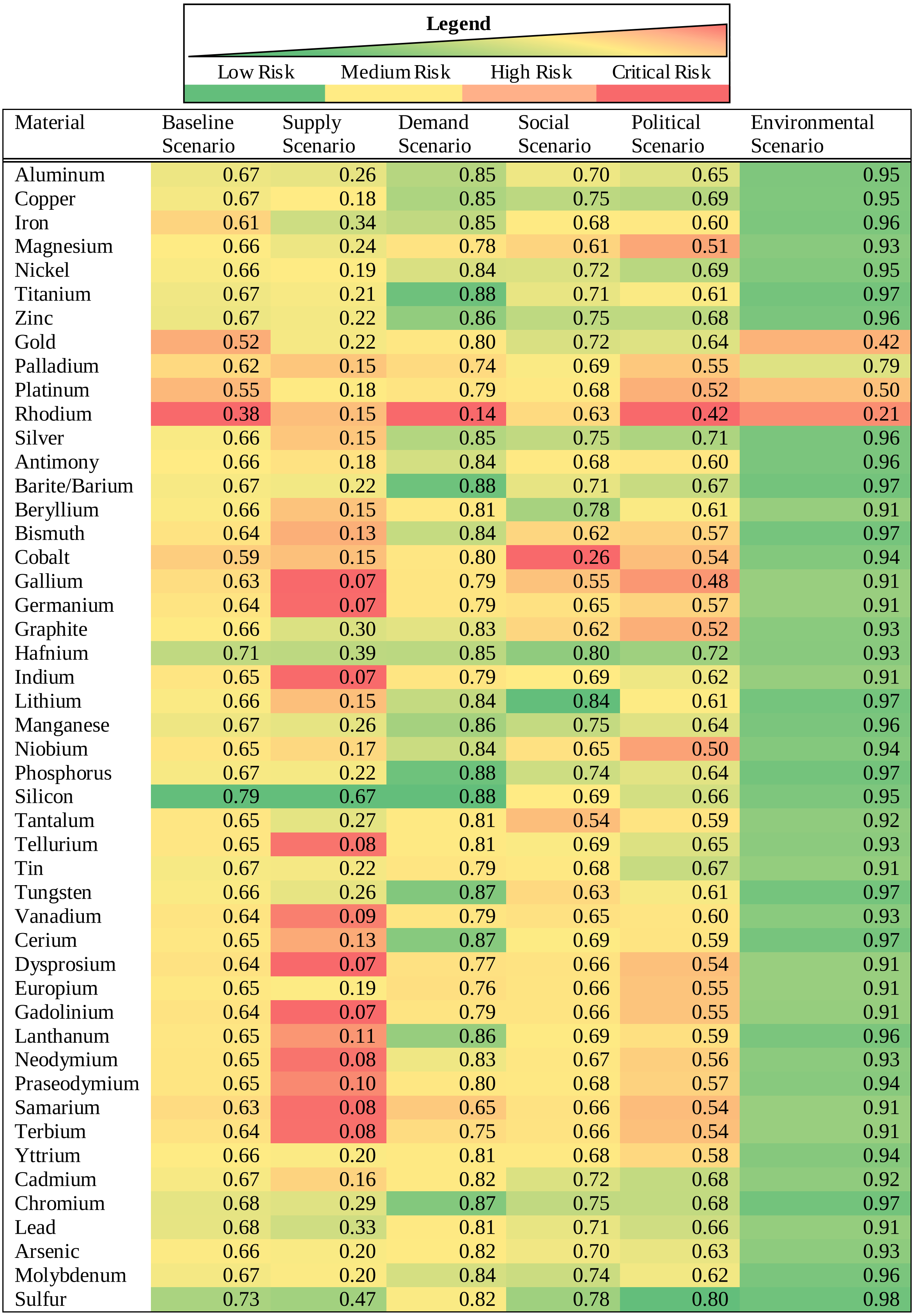
The environmental metrics data for all the materials were collected from Nuss & Eckelman (2014). For graphite data for Global Warming Potential and Cumulative Energy Demand was taken from Althaf & Babbitt (2021). Data for silicon, sulfur, and phosphorus was not available for any of the environmental metrics.

5 RESULTS

As mentioned in the previous chapter, eighteen metrics were established from the literature, each belonging to a group of risk: supply, demand, socio-political and environmental. They help quantify the risk related to these areas and detect bottlenecks of the materials by simulating different disruption scenarios. In Figure 4 below, the final risk scores are presented for each material, for each scenario.

From the results shown in Figure 4, in the baseline scenario where all factors pose an equal risk, it is noticeable that the impact is stronger in the precious metals, more specifically rhodium, platinum, palladium, and gold.

Figure 4. Risk scores identified with the TOPSIS method presented as a heat map pointing out the highest and the lowest scores for the six analyzed scenarios



Material	Baseline Scenario	Supply Scenario	Demand Scenario	Social Scenario	Political Scenario	Environmental Scenario
Aluminum	0.67	0.26	0.85	0.70	0.65	0.95
Copper	0.67	0.18	0.85	0.75	0.69	0.95
Iron	0.61	0.34	0.85	0.68	0.60	0.96
Magnesium	0.66	0.24	0.78	0.61	0.51	0.93
Nickel	0.66	0.19	0.84	0.72	0.69	0.95
Titanium	0.67	0.21	0.88	0.71	0.61	0.97
Zinc	0.67	0.22	0.86	0.75	0.68	0.96
Gold	0.52	0.22	0.80	0.72	0.64	0.42
Palladium	0.62	0.15	0.74	0.69	0.55	0.79
Platinum	0.55	0.18	0.79	0.68	0.52	0.50
Rhodium	0.38	0.15	0.14	0.63	0.42	0.21
Silver	0.66	0.15	0.85	0.75	0.71	0.96
Antimony	0.66	0.18	0.84	0.68	0.60	0.96
Barite/Barium	0.67	0.22	0.88	0.71	0.67	0.97
Beryllium	0.66	0.15	0.81	0.78	0.61	0.91
Bismuth	0.64	0.13	0.84	0.62	0.57	0.97
Cobalt	0.59	0.15	0.80	0.26	0.54	0.94
Gallium	0.63	0.07	0.79	0.55	0.48	0.91
Germanium	0.64	0.07	0.79	0.65	0.57	0.91
Graphite	0.66	0.30	0.83	0.62	0.52	0.93
Hafnium	0.71	0.39	0.85	0.80	0.72	0.93
Indium	0.65	0.07	0.79	0.69	0.62	0.91
Lithium	0.66	0.15	0.84	0.84	0.61	0.97
Manganese	0.67	0.26	0.86	0.75	0.64	0.96
Niobium	0.65	0.17	0.84	0.65	0.50	0.94
Phosphorus	0.67	0.22	0.88	0.74	0.64	0.97
Silicon	0.79	0.67	0.88	0.69	0.66	0.95
Tantalum	0.65	0.27	0.81	0.54	0.59	0.92
Tellurium	0.65	0.08	0.81	0.69	0.65	0.93
Tin	0.67	0.22	0.79	0.68	0.67	0.91
Tungsten	0.66	0.26	0.87	0.63	0.61	0.97
Vanadium	0.64	0.09	0.79	0.65	0.60	0.93
Cerium	0.65	0.13	0.87	0.69	0.59	0.97
Dysprosium	0.64	0.07	0.77	0.66	0.54	0.91
Europium	0.65	0.19	0.76	0.66	0.55	0.91
Gadolinium	0.64	0.07	0.79	0.66	0.55	0.91
Lanthanum	0.65	0.11	0.86	0.69	0.59	0.96
Neodymium	0.65	0.08	0.83	0.67	0.56	0.93
Praseodymium	0.65	0.10	0.80	0.68	0.57	0.94
Samarium	0.63	0.08	0.65	0.66	0.54	0.91
Terbium	0.64	0.08	0.75	0.66	0.54	0.91
Yttrium	0.66	0.20	0.81	0.68	0.58	0.94
Cadmium	0.67	0.16	0.82	0.72	0.68	0.92
Chromium	0.68	0.29	0.87	0.75	0.68	0.97
Lead	0.68	0.33	0.81	0.71	0.66	0.91
Arsenic	0.66	0.20	0.82	0.70	0.63	0.93
Molybdenum	0.67	0.20	0.84	0.74	0.62	0.96
Sulfur	0.73	0.47	0.82	0.78	0.80	0.98

Source: Own work.

What contributes to this is the low global reserve and low ore concentration and at the same time, they rely on by-product production. According to one study, when considering yearly average prices over the last 50 years, metals and minerals with by-product production have had more volatile prices than those produced primarily as main products. The consequences appear to be significant as well, with by-products being around 50% more volatile on average (Redlinger & Eggert, 2016). Furthermore, existing or projected operations that might easily create by-product minerals from their deposits will not do so in certain circumstances simply because it is not cost-effective.

Precious metals have considerable environmental consequences on a per kg basis, including all of the environmental metrics. Metals present in low abundance require more energy and resources to be extracted and are typically characterized by high prices, which are considered by the economic allocation methods applied by the life cycle data (Ecoinvent Simapro) used to model environmental impact (Althaf & Babbitt, 2021). The data used in this thesis for the environmental metrics were adopted from studies that used this database, so the outcome makes sense. For the baseline scenario, the most notable materials that cause attention are the platinum group of materials, however, cobalt, iron, and some rare earth follow after with similar risk scores.

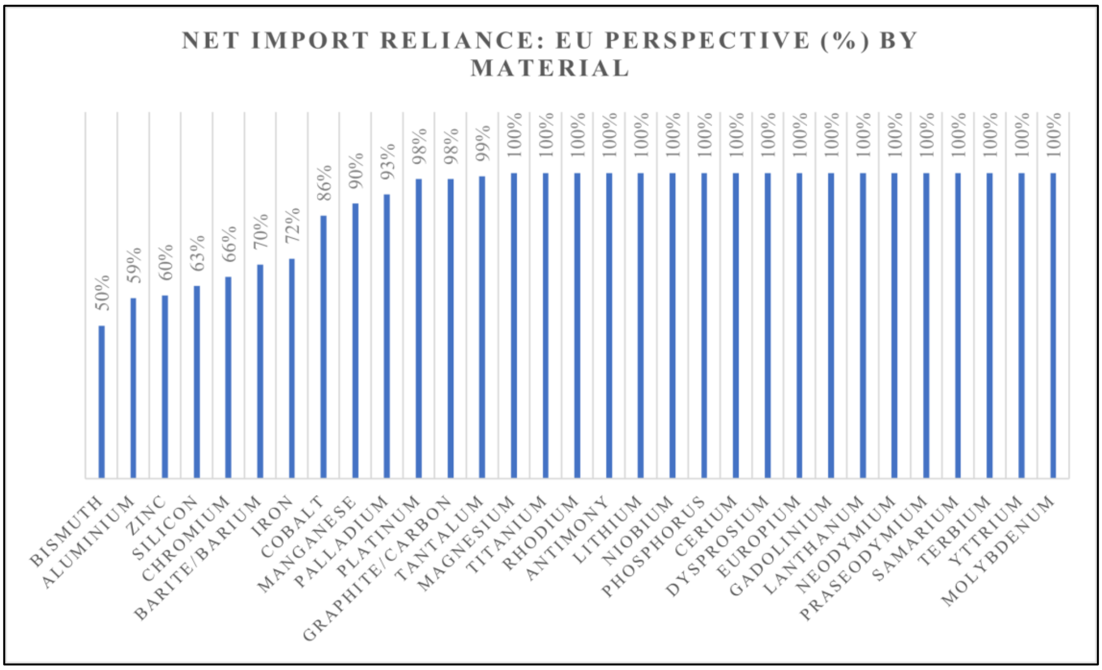
Under different scenarios, several outcomes could be detected. In a scenario where some event causes an increased demand for electronics and decreased production of needed materials, the platinum group is replaced with gallium, germanium, graphite, indium, tellurium, vanadium, cerium, dysprosium, gadolinium, lanthanum, neodymium, praseodymium, samarium, and terbium. These metals are used heavily in the electronics industry, have a low abundance in ores, and are almost exclusively obtained as byproducts in a small number of geographical areas. Since by-products ultimately depend on the production of the parent metal, moving production to other regions or scaling it up may not be technically or economically feasible in the event of sudden disruption to a major supplier country or trading partner (Althaf & Babbitt, 2021).

Next, in a scenario where global disruptions lead to economic downturns followed by material surges as economies try to recover and function as before, rhodium is again noted as a particularly high risky material. Besides rhodium, all other materials that are part of the platinum metals have the highest impact in scenarios when the priority of preserving the environment is put last, causing an escalation of environmental dangers associated with material production. From a social perspective, some events such as Covid - 19 pandemic or internal political conflicts in nations with weak governance and unstable political systems, can increase the danger to society - particularly from forced labor, layoffs, poor working conditions, and workers' disease. Social risks are extremely high for cobalt, followed by tantalum, gallium, and several REE, and when looking at the values for the Social Hotspot metric, manganese, tin, and bismuth also have high impacts. These risks originate from the geographical concentration of production in countries with weak standards for governance, health and safety, and basic human and labor rights. Cobalt and tin share the same characteristics when it comes to this and both materials belong to the group of “conflict materials”, as their commercial production and trade have fueled armed conflicts and violence in countries like the Democratic Republic of Congo (Young, 2018).

When some disruption leads to geopolitical barriers to material accessibility, risks are particularly high for several REE, platinum metals, magnesium, niobium, graphite, gallium, germanium, cobalt, and bismuth. From the EU's perspective, these risks are amplified by the EU's significant net import reliance. In theory, a more diverse supply chain, both concerning the number of producing countries and the types of extraction infrastructure, can be expected to reduce risks. These materials also have a strong demand in the electronics industry in general, which may be problematic since their demand risks may be increased by the demand for electronic technology during disruption events. On the other side, this may be beneficial in the sense that the products with electronic components represent a potential source for the 'urban mining' recovery of materials, as discussed in the previous chapter.

As domestic consumption of all metal ores in Europe continues to rise (340 million tons in 2017 compared to 317 million tons in 2008 and 250 million tons in 1970), domestic extraction of metal ores has significantly decreased. As a result, a growing portion of metal resources (ores and intermediate products) are being imported. Thirty out of forty-eight materials analyzed have net import reliance greater than 50% (Figure 5)

Figure 5. Net import reliance from the EU’s perspective, (%) by material



Source: Own work.

5.1 Smart meter implications

Two important transformations in energy production and consumption have occurred in the last decades. First, there has been a rapid acceleration of renewable energy generation technologies, including wind and solar technologies, and, as a result, new technologies for more efficient electricity consumption patterns have appeared, for example, smart grids and smart meters, which are being installed more and more on a global scale. Smart meters are devices that balance the diverse electricity availability of renewable energy production technologies and interact via wireless sensor networks to provide real-time communication between the producer, distribution operator, and consumer, all of whom are linked by sensors with integrated processors (Ding, Cooper, Pasquina, & Fici-Pasquina, 2011). Elements like gallium, indium, and silicon are used in the manufacture of such devices, as are rare earth elements such as hafnium, neodymium, and praseodymium. They are complex products that have over two hundred components and around 80 % are electronic components (depending on the meter) that are directly affected by the risks related to the raw material (Markizeti & Heringer, 2021). Analysis was done on the AM550 (single-phase) meter, based on the April 2019 bill of material (BOM) and the connection was done between the critical raw materials and how much of those materials are in the meter as shown in Table 5.

Table 5. Content of critical materials of the electricity meter, analyzed on 95 % by mass.

EU Critical Raw Materials	**Mass per analyzed meter (mg)**	**No. of analyzed meter unique components**
Ruthenium	0,7	49
Phosphor	26,3	32
Boron	0,4	58
Palladium	1,4	66
Magnesium	2,3	53
Antimony	30,2	16 + 4 solders
Cobalt	1,4	12
Silicon	6.025	118
Gallium	0,07	1
Neodymium	13,2	13
Germanium	0,000	2 solders
Indium	1,9	4 solders
Platinum	37,0	2
Praseodymium	0,6	5
Bismuth	8,1	62 + 4 solders
Tungsten	2,65	3
Vanadium	0,001	1
Beryllium	1,8	1
Lithium	0,9	1
Titanium	8.000	15(polycarbonate)
Strontium	3	25

Source: Markizeti & Heringer (2021, p. 13).

In the scope of this thesis, another meter was analyzed, which is one of the most purchased meters for the next year - IE.5 three-phase meters for smart applications and an analysis of some of the components was done. The first selection criteria were that the components being analyzed make the 80% of the price of the meter. Then data availability was checked, and seven components were finally analyzed. In Table 6 the components and what materials they are made of are presented.

Table 6. Components from IE.5 smart meter, materials they are composed of, and risk scores calculated with the TOPSIS method for the baseline scenario

Component 1	Risk Scores												
Symbol	**Si**	**Cu**	**Sb**	**Zn**	**Bi**	**Gr**	**P**	**Ti**	**Ce**	**Pb**	**Sn**	**Mo**	**Ag**
Baseline Scenario	0.79	0.67	0.66	0.67	0.64	0.66	0.67	0.67	0.65	0.68	0.67	0.67	0.66
Supply Scenario	0.67	0.18	0.18	0.22	0.13	0.3	0.22	0.21	0.13	0.33	0.22	0.2	0.15
Demand Scenario	0.88	0.85	0.84	0.86	0.84	0.83	0.88	0.88	0.87	0.81	0.79	0.84	0.85
Social Scenario	0.69	0.75	0.68	0.75	0.62	0.62	0.74	0.71	0.69	0.71	0.68	0.74	0.75
Political Scenario	0.66	0.69	0.60	0.68	0.57	0.52	0.64	0.61	0.59	0.66	0.67	0.62	0.71
Environmental Scenario	0.95	0.95	0.96	0.96	0.97	0.93	0.97	0.97	0.97	0.93	0.91	0.96	0.96
Component 2	Risk Scores												
Symbol	**Gr**	**Si**	**Cu**	**P**	**Sn**	**Au**	**Ni**						
Baseline Scenario	0.66	0.79	0.67	0.67	0.67	0.52	0.66						
Supply Scenario	0.3	0.67	0.18	0.22	0.22	0.22	0.19						
Demand Scenario	0.83	0.88	0.85	0.88	0.79	0.8	0.84						
Social Scenario	0.62	0.69	0.75	0.74	0.68	0.72	0.72						
Political Scenario	0.52	0.66	0.69	0.64	0.67	0.64	0.69						
Environmental Scenario	0.93	0.95	0.95	0.97	0.91	0.42	0.95						
Component 3	Risk Scores												
Symbol	**Si**	**Sn**	**Ba**	**Al**	**Cr**	**Cu**	**Gr**	**Ni**	**Ti**	**Co**	**Fe**	**Mn**	
Baseline Scenario	0.79	0.67	0.67	0.67	0.68	0.67	0.66	0.66	0.67	0.59	0.61	0.67	
Supply Scenario	0.67	0.22	0.22	0.26	0.29	0.18	0.3	0.19	0.21	0.15	0.34	0.26	
Demand Scenario	0.88	0.79	0.88	0.85	0.87	0.85	0.83	0.84	0.88	0.8	0.85	0.86	
Social Scenario	0.69	0.68	0.71	0.7	0.75	0.75	0.62	0.72	0.71	0.26	0.68	0.75	
Political Scenario	0.66	0.67	0.67	0.65	0.68	0.69	0.52	0.69	0.61	0.54	0.6	0.64	
Environmental Scenario	0.95	0.91	0.97	0.95	0.97	0.95	0.93	0.95	0.97	0.94	0.96	0.96	

Continued

Table 5. Components from IE.5 smart meter, materials they are composed of, and risk scores calculated with the TOPSIS method for baseline scenario (continued)

Component 4	Risk Scores										
Symbol	**Fe**	**Si**	**Au**	**Gr**	**P**	**Cu**	**Ag**	**Zn**	**Sn**		
Baseline Scenario	0.61	0.79	0.52	0.66	0.67	0.67	0.66	0.67	0.67		
Supply Scenario	0.34	0.67	0.22	0.3	0.22	0.18	0.15	0.22	0.22		
Demand Scenario	0.85	0.88	0.8	0.83	0.88	0.85	0.85	0.86	0.79		
Social Scenario	0.68	0.69	0.72	0.62	0.74	0.75	0.75	0.75	0.68		
Political Scenario	0.6	0.66	0.64	0.52	0.64	0.69	0.71	0.68	0.67		
Environmental Scenario	0.96	0.95	0.42	0.93	0.97	0.95	0.96	0.96	0.91		
Component 5	Risk Scores										
Symbol	**Si**	**Au**	**Zn**	**Pd**	**Cu**	**Gr**	**Au**	**Ag**	**Ni**	**Fe**	**P**
Baseline Scenario	0.79	0.52	0.67	0.62	0.67	0.66	0.52	0.66	0.66	0.61	0.67
Supply Scenario	0.67	0.22	0.22	0.15	0.18	0.3	0.22	0.15	0.19	0.34	0.22
Demand Scenario	0.88	0.8	0.86	0.74	0.85	0.83	0.8	0.85	0.84	0.85	0.88
Social Scenario	0.69	0.72	0.75	0.69	0.75	0.62	0.72	0.75	0.72	0.68	0.74
Political Scenario	0.66	0.64	0.68	0.55	0.69	0.52	0.64	0.71	0.69	0.6	0.64
Environmental Scenario	0.95	0.42	0.96	0.79	0.95	0.93	0.42	0.96	0.95	0.96	0.97
Component 6	Risk Scores										
Symbol	**Zn**	**Cu**	**Fe**	**Ag**	**Cu**	**P**	**Sn**	**Gr**	**Si**		
Baseline Scenario	0.67	0.67	0.61	0.66	0.67	0.67	0.67	0.66	0.79		
Supply Scenario	0.22	0.18	0.34	0.15	0.18	0.22	0.22	0.3	0.67		
Demand Scenario	0.86	0.85	0.85	0.85	0.85	0.88	0.79	0.83	0.88		
Social Scenario	0.75	0.75	0.68	0.75	0.75	0.74	0.68	0.62	0.69		
Political Scenario	0.68	0.69	0.6	0.71	0.69	0.64	0.67	0.52	0.66		
Environmental Scenario	0.96	0.95	0.96	0.96	0.95	0.97	0.91	0.93	0.95		

Continued

Table 5. Components from IE.5 smart meter, materials they are composed of, and risk scores calculated with the TOPSIS method for baseline scenario (continued)

Component 7	Risk Scores									
Symbol	**Ni**	**P**	**S**	**Mn**	**Si**	**Fe**	**Cr**	**Gr**	**Sn**	
Baseline Scenario	0.66	0.67	0.73	0.67	0.61	0.61	0.68	0.66	0.67	
Supply Scenario	0.19	0.22	0.47	0.26	0.67	0.34	0.29	0.3	0.22	
Demand Scenario	0.84	0.88	0.82	0.86	0.88	0.85	0.87	0.83	0.79	
Social Scenario	0.72	0.74	0.78	0.75	0.69	0.68	0.75	0.62	0.68	
Political Scenario	0.69	0.64	0.8	0.64	0.66	0.6	0.68	0.52	0.67	
Environmental Scenario	0.95	0.97	0.98	0.96	0.95	0.96	0.97	0.93	0.91	

Source: Own work.

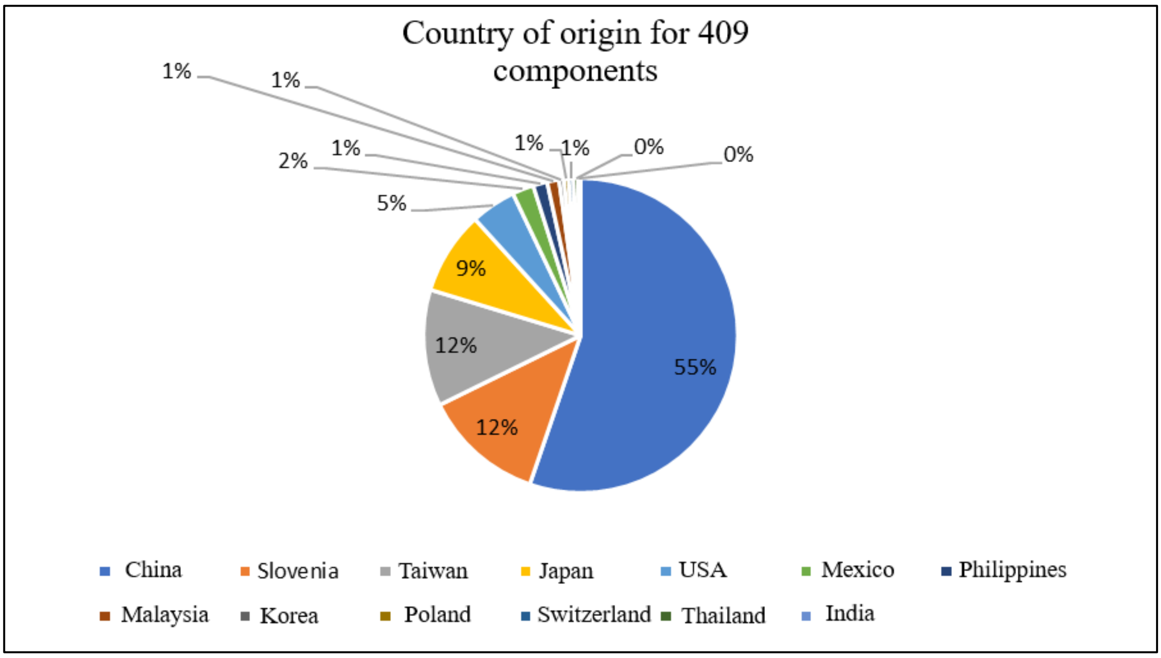
For each material, there is a risk score for six different scenarios calculated with the TOPSIS method as described in the previous chapter. These risk scores can be an indicator to detect a potential risk in a certain disruption event that could lead to a risk to a particular material, which could influence the physical availability of the material, price, and increases in the environmental footprint because of regulations would not fulfill the criteria to purchase some components.

Each component has a different mix of materials, and for each scenario, we get different scores that point to certain potential risks. This can serve as a first step toward employing risk management practices. Detecting and identifying the potential areas of risk gives a signal of where to look and what to examine so that strategies are put in place to prevent, avoid or mitigate the risk.

In 2019 components for all meters were bought from 85 different manufacturers from 13 different countries, as seen in Figure 6 China is leading with 55%, Slovenia and Taiwan following with 12 %, which is positive news that the second in line is Slovenia, and that percentage must go up. However, at the same time, six countries have a share of 96 %, and that is a sign of huge geographic concentration and brings high risk.

When it comes specifically to the IE.5 meter, out of seven components analyzed, three of the components have their country of origin in China, three in the United States, and one in Taiwan, so not only that China is a leader in having reserves of most of the REE and other critical raw material, but also they are also the main production of components are in China, United States, Taiwan, as we could see from the Figure 6 as well.

Figure 6. Country of origin for purchased components in 2019



Source: Markizeti & Heringer (2021,p. 25).

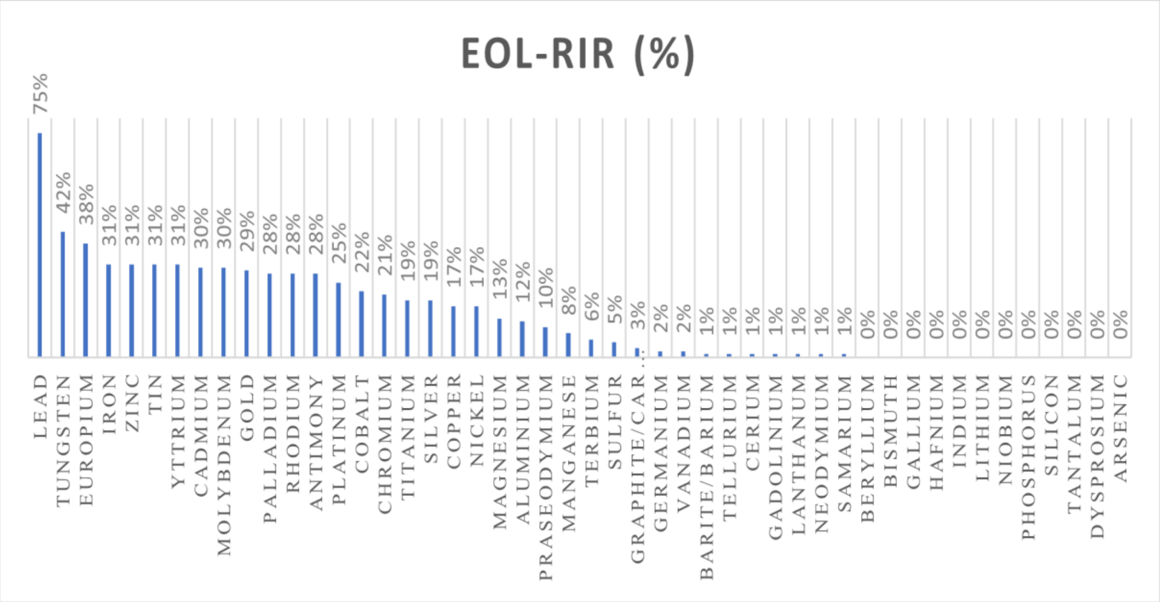
5.2 Sustainable mitigation strategies

- Recycling

Recycling remains the most popular method for extending the life of metals, safeguarding primary raw material inputs, and minimizing the need for metal ore extraction and the associated harmful environmental effects. High recycling levels have been achieved for several metals. Additionally, scrap accounts for more than half of the total input to manufacturing and smelting for lead, copper, and silver, and is around 35% and 50% for steel, aluminum, and zinc worldwide. However, due to the steady rise in global demand, the quantities of recycled metals now available cannot entirely replace primary metals. Fewer than 30% of the sixty metals that were evaluated in one assessment had recycling rates above 50%, although many of those metals are essential for the development of clean technologies, such as the batteries for hybrid automobiles or the magnets in wind turbines (Nuss & Eckelman, 2014).

From the data used for this thesis, only one material has an End-of-Life Recycling Input Rate bigger than 50% in the EU, and that is lead as shown in Figure 7. Around 25% of the analyzed materials used as input in the EU economy are used only as primary raw materials.

Figure 7. End of Life Recycling Input Rate in (%) by material



Source: Own work.

Santillán-Saldivar et al. (2021) extended the Geopolitical Supply Risk (GeoPolRisk) method to incorporate the risk-mitigating potential of domestic recycling, furthering the discussion of "circular economy" strategies for the criticality of materials.

The Geopolitical Supply Risk method is trying to include supply risk assessment of critical raw materials as a complement to environmental life cycle assessment (LCA). The use of the expanded GeoPolRisk method on the following materials: beryllium, boron, cobalt, gallium, hafnium, indium, niobium, germanium, magnesium, graphite, palladium, platinum, iridium, ruthenium, REE, silicon, and tantalum. Mainly materials that are used for information and communication technologies in the European Union. This paper supports the idea that recycling can reduce the risk of raw material supply. By reducing pressure on primary sourcing, they believe recycling can reduce supply risk. But because the GeoPolRisk indicator is regionalized, they add another layer to the evaluation by considering the relative geopolitical (in) stability of both primary and secondary sources. The two processes whereby recycling might impact supply risk are taken into account by the expanded GeoPolRisk method: first, a decrease in overall imports (the "reduction effect"), and second, a potential redistribution of the import supply mix (the "redistribution effect"). Therefore, recycling should preferably be done locally, and the recycled material should be reintroduced into the domestic economy to optimize risk reduction. Locally extracted, and manufactured raw materials have the power to significantly reduce production costs while also boosting local economies. Locally sourcing raw materials is a strategic move for both countries and businesses, having obvious advantages such as the decrease in shipping costs for transportation and handling the associated emissions.

Another option besides locally recycling and compared to utilizing raw materials, importing recycled materials from other countries may be better for the environment, but this does not fully mitigate the risk of supply associated with geopolitics. Importing recycled materials from geopolitically unstable countries or areas might make supply risk worse. The import supply mix should be taken into account to further reduce supply risk, especially because the redistribution impact might occasionally outweigh the reduction effect. For instance, importing crucial resources from conflict zones is often denounced as unethical behavior, with serious consequences if done so, despite being from a short-sighted economic perspective deemed a cost-effective raw material sourcing (European Commission, 2017).

In one study on recycling printed circuit boards (PCB), they suggested a small-molecule assisted method that was based on a dynamic reaction approach for recycling waste circuit boards that is both effective and ecologically friendly. At temperatures below 200 °C, thermoset resins containing ester groups in discarded circuit boards were easily dissolved by the transesterification reaction. As a result, electronic components possessing electronic qualities may be easily separated from circuit boards. Experiment findings indicated that this method could recycle a wide range of commercial PCBs, including boards built of common epoxy-anhydride and polyester resin substrates. Since PCBs are an essential component of smart meters and other electronic devices, it is important to consider recycling. This study proves the possibility of it, and even more importantly it is done in an environmentally friendly way (Chen et al., 2019).

- Recovery as by-products

The behavior of a few elements (bismuth, antimony, selenium, arsenic, and tellurium) through the primary copper pyrometallurgical supply chain has been researched. Critical materials in ppm or g/tonne concentrations inside orebodies are not frequently reported, resulting in a lack of understanding about accessible resources. Moreover, the distribution of these critical materials in mineral processing plants is not well studied due to low concentrations. This means a lack of process mineralogy to detect host minerals for critical elements that may be recovered. The potential annual availability of selenium and tellurium in copper anodes was predicted to be 2-3 and 4-5 times, respectively, of the world's current annual production of the metals. Advanced recovery of tellurium and selenium using slimes has been studied (primarily in Asia and Europe). More research in this area should be encouraged, along with an understanding of why more selenium and tellurium are not now recovered. Ion exchange is a commercial method for removing bismuth and antimony from electrolytes. Manufacturing a salable product from the eluate should be encouraged, as should research in this field. Extracting these elements as by-products is a sustainable way to ensure their availability, for example in a scenario when there is a demand increase, the risk of unavailability can be mitigated.

But of course, the products that generate the highest income or profit for a business receive the most attention. The potential values of copper, gold, silver, selenium, tellurium, arsenic, antimony, and bismuth incorporated in three refinery anodes were estimated to investigate the potential of extraction of these metals from them. As assumed, the potential values for copper, gold, and silver outweigh those for the other elements. Therefore, in a refinery, the attention devoted to selenium, tellurium, arsenic, antimony, and bismuth is generally related to how these elements influence copper, gold, and silver production, with the emphasis on contamination removal rather than by-product creation. The refinery removes selenium, tellurium, arsenic, antimony, and bismuth by the treatment of slimes or a part of the electrolyte. If the economics of recovery is more beneficial than disposal, then removal may result in a salable product of these elements (Moats et al., 2021).

According to the data gathered for this thesis, the global reserve for antimony, bismuth tellurium and arsenic summed up is 9% of the reserve of copper, so an obvious risk mitigation measure would be to extract them as byproducts of copper.
Finally, a better knowledge of the life cycle environmental implications of mining these components will be required to develop policies and strategies that will contribute to sustainable extraction. Because all of these elements are byproducts, improving life cycle allocation methodologies will be essential to ensure that it can be properly quantified the environmental footprint associated with extracting these elements.

- Urban and landfill mining

When it comes to the physical availability of materials, an interesting thing is that huge quantities of metals that are "temporarily" stored in buildings, infrastructure, and other long-lasting goods are increasingly seen as potential sources of metallic supplies in the future. Therefore, buildings and goods must be planned, built, and developed in a way that will make it easier to recover and recycle metallic compounds, by making products (such as cars, electrical and electronic gadgets, etc.) that are simple to disassemble. A team effort involving engineers (civil, materials, process, etc.), architects, and metallurgy researchers is also needed to develop new, highly effective, and economically feasible metal recovery techniques and systems (Awasthi & Li, 2017). Since most of the emissions, freshwater eutrophication, and human toxicity consequences occur during material extraction, urban and landfill mining can mitigate the environmental risks by being a source of material supply without the negative effects such as sinkholes, contamination of soil, erosion, groundwater, and loss of biodiversity by the chemicals emitted from mining processes.

- Reuse

To evaluate the potential for secondary materials to replace primary demand, Busch, Dawson, & Roelich (2017) made a model that demonstrates this, and it is one of the rare studies that explore reusing as a mitigation strategy. At a component level, they reuse lithium-ion (Li-ion) batteries from electric vehicles for grid-connected storage of an island's power production, without remanufacturing being involved in this process. They examined recycling neodymium from the composite (neodymium iron boron) used for permanent magnets in engines and wind turbines, lithium and cobalt from Li-ion batteries, and platinum from catalytic converters and hydrogen fuel cells. They developed two scenarios for an island's low-carbon energy and transportation transition, based on a hydrogen fuel cell or electric battery vehicle choice for transportation. The first scenario is that for transportation transition electric cars with batteries are used, and the second scenario is the transportation transition includes cars powered by hydrogen fuel cells. They assumed a 90% recycling rate for platinum-based on commercially established high collection rates of catalytic converters from end-of-life cars and great recycling process efficiency. Based on laboratory-established methodologies, recycling rates for lithium and cobalt from Li-ion batteries were assumed to be 70% and 90%, respectively. Because of a lack of incentives, neodymium recycling rates were then much less than 1%. Given that the feasibility of neodymium recycling surpasses 90% efficiency, they estimated an overall recycling rate of 80%. They make projections that recycling lithium and cobalt can significantly decrease primary demand beginning in 2025 when the first generation of Li-ion batteries approaches the end of their lifespan and are ready for recycling. From 2033 onwards, there is more secondary lithium input than primary lithium input in the first described scenario, with more than forty-three tonnes of lithium recycled in that year. A similar effect can be seen with neodymium in the second described situation, except that the delay is larger since NdFeB motors have a 13-year lifetime compared to Li-ion batteries' 8-year. The impact of recycling thus becomes large only after 2030, yet secondary input already outnumbers original input by more than 1.1 tonnes in 2033. Since platinum is also used in today's generation of end-of-life internal combustion engine cars, platinum recycling is not delayed is platinum recycling. In the case of the second described scenario, the primary demand for platinum is reduced as a result.

Reusing Li-ion batteries from electric cars for grid-connected storage has the potential to significantly reduce the demand for lithium and cobalt. The drop in lithium demand, including both demand (cars and storage), shows how reusing batteries from cars to grid-connected storage can decrease primary lithium consumption by up to 30,000 kg per year beyond 2030. Taking only the drop in storage demand into account, the reuse of batteries can replace the primary demand for lithium in storage after 2033 (Busch et al., 2017).

Watari et al. (2020) point out in their paper that almost no attention is put into research on the effect of reuse, remanufacture, and lifetime extension on mitigating risks, and the case of reusing Li-ion batteries should encourage future exploration in this field because it has great potential. Critical concerns remain unanswered, such as how quickly and to what degree this raw material transition toward secondary materials can be accomplished while supplying enough resources to meet the rising world demand. Many scientists and researchers in the mining industry think that society and economies will continue to require primary resources, including metals from mining operations, in the short, medium, and long term, despite continual progress in recycling activities (Sillanpää & Ncibi, 2019).

5.3 Limitations of the research and future thoughts

As mentioned in the data collection chapter, for some materials it was difficult to obtain data, especially for the environmental metrics, and for some data was available for 2021 and some from 2014, so this is one limitation. One noticeable thing was the silicon, where in all scenarios the risk scores were relatively good, nothing stood out and did not point to some potential risk, global reserves are not under threat, however in the media and the academic circles more and more is reported about the consequences on the environment from silicon production (Saevarsdottir, Kvande, & Magnusson, 2021). So, the quantitative results from this thesis in most of the cases match the qualitative conclusions and discussions from the literature, nevertheless, aligned perspectives are necessary to make a quality analysis of the potential risks.

One of the issues regarding analyzing the components, materials, suppliers, and all involved parties in the supply chain to get a clear overview, early detection of some problems, make improvements, etc., is that collection of such data is manually gathered and a general lack of responsiveness from suppliers' side. Iskraemeco has been working on supply chain transparency for many years and has concluded that manual data collection is time-consuming, the data is not verified, and many errors are found in supplier responses. The only way to keep the goal of supply chain transparency is through a tool (which also includes data verification) that can make that process automatized. To achieve this, a Supplier Portal was created where all data regarding suppliers, materials origin, standard compliance, etc. is in one place and hopefully will allow for easier manipulation of the data.
The industry in general does not support any similar system for tracking materials back to their origin, and this request is not backed by any EC Guidelines, legislation, or other means. The majority of materials are acquired on the "materials market," which is comparable to the stock market, and purchasers have no insurance on the material background. So, talking about and promoting fair labor standards, environmental sensitivity, and supply chain transparency can help raise awareness of greater transparency, also on material origin.

For future research, the focus should be put on design improvements to not only make a product (in this case a smart meter) easy to recycle, but also reuse and remanufacture. There are obvious limitations because more or less the parts are specially created for a certain meter – and their lifetime is approximately 20 years, and then it is very unlikely that the same parts will be reused creating a meter, but very new solutions will be

feasible. However, innovating new solutions is a challenge that many companies and researchers are striving to achieve every day, so nothing is impossible.
Substitution and circular economy activities can help mitigate the risk of physical unavailability, risk of delayed deliveries, and environmental footprint, and one of the crucial things for the short-term future to enable this should be an exploration of European potential for extraction and production of critical raw materials.

CONCLUSION

The global crisis with part shortages, price increases, and longer lead times in the electronic components supply chain was highlighted by the COVID-19 pandemic and brought even more attention to the gaps and risks that disrupted the supply chains. Smart meters, as devices with more than 80% of the components being electronic components, are and will be facing the consequences of the supply-demand mismatch, price spikes, and the difficulty to get certain components. To tackle that problem, an overview and mapping of the risks related to the raw materials from a supply, demand, socio-political and environmental point of view were done. Risk management and processes were defined, as well as an overview was given of the critical raw materials and legislations that regulate the environmental consequences of the extraction, production, consumption, and import of these materials. A multi-criteria analysis using the TOPSIS method was performed to predict possible risks for material supply chains in the electronics industry, both during normal operation and from unexpected interruptions. Circular economy was defined and presented as a future concept that will be employed by all industries. Sustainability mitigation strategies such as recycling, reusing, and remanufacturing were explored, and practical examples were presented. A potential resource for getting waste to recycle is the concept of urban and landfill mining.

The results showed that the platinum group of metals, more specifically rhodium, platinum, palladium, and gold have a high risk in a baseline scenario. What contributes to this is the low global reserve and low ore concentration and at the same time, they rely on by-product production. Looking from a social perspective, risks are extremely high for cobalt, followed by tantalum, gallium, and several REE, and for the supply scenario gallium, germanium, graphite, indium, tellurium, and REE are affected the most. Recycling can mitigate supply risks, geopolitical risks, and social risks, while urban and landfill mining can help with mitigating environmental risks. Reuse as a strategy, as well as recovery of materials as a by-product can help mitigate the risk of physical unavailability and demand for materials. This mapping of the risks and how the sustainability strategies can help mitigate those risks is just an indicator in which direction further research and analysis should be done, and what activities should be placed to deal with a crisis with the least consequences possible.

REFERENCE LIST

1. Allwood, J. M., Ashby, M. F., Gutowski, T. G., & Worrell, E. (2011). Material efficiency: A white paper. *Resources, Conservation and Recycling*, *55*(3), 362–381. https://doi.org/10.1016/j.resconrec.2010.11.002
2. Almajali, D., Mansour, K., Masa'deh, R., & Maqableh, M. (2016). The Impact of Electronic Supply Chain Management Usage on Firm's Performance. *International Journal of Communications, Network and System Sciences*, *9*(6), 280–293. https://doi.org/https://doi.org/10.4236/ijcns.2016.96025
3. Althaf, S., & Babbitt, C. W. (2021). Disruption risks to material supply chains in the electronics sector. *Resources, Conservation & Recycling*, *167*, 105248. https://doi.org/10.1016/j.resconrec.2020.105248
4. Ampudia, M., Bua, G., Kapp, D., & Salakhova, D. (2022). The role of speculation during the recent increase in EU emissions allowance prices. *ECB Economic Bulletin*, (3).
5. Aven, T. (2016). Risk assessment and risk management : Review of recent advances on their foundation. *European Journal of Operational Research*, *253*(1), 1–13. https://doi.org/10.1016/j.ejor.2015.12.023
6. Awasthi, A. K., & Li, J. (2017). An overview of the potential of eco-friendly hybrid strategy for metal recycling from WEEE. *Resources, Conservation and Recycling*, *126*, 228–239. https://doi.org/10.1016/j.resconrec.2017.07.014
7. Bailey, T., Barriball, E., Dey, A., & Sankur, A. (2019). *A practical approach to supply-chain risk management.* Retrieved from https://www.mckinsey.com/business-functions/operations/our-insights/a-practical-approach-to-supply-chain-risk-management
8. Balioti, V., Tzimopoulos, C., & Evangelides, C. (2018). Multi-Criteria Decision Making Using TOPSIS Method Under Fuzzy Environment. Application in Spillway Selection. *Proceedings*, *2*, 1–8. https://doi.org/10.3390/proceedings2110637
9. Barker, A. V. (2019). Fertilizers. In P. Worsfold, C. Poole, A. Townshend, & M. Miró (Eds.), *Encyclopedia of Analytical Science* (pp. 134–144). Oxford: Academic Press. https://doi.org/https://doi.org/10.1016/B978-0-12-409547-2.00142-6
10. BBC News. (2021). *Venezuela crisis: How the political situation escalated*. Retrieved July 17, 2022, from https://www.bbc.com/news/world-latin-america-36319877
11. Blengini, G. A., Latunussa, C. E. L., Eynard, U., Torres de Matos, C., Wittmer, D., Georgitzikis, K., … Pennington, D. (2020). *Study on the EU's list of Critical Raw Materials (2020) Final Report*. Retrieved July 17, 2022, from https://op.europa.eu/en/publication-detail/-/publication/c0d5292a-ee54-11ea-991b-01aa75ed71a1/language-en
12. Bocken, N. M. P., Short, S. W., Rana, P., & Evans, S. (2014). A literature and practice review to develop sustainable business model archetypes. *Journal of*

Cleaner Production, *65*, 42–56. https://doi.org/10.1016/j.jclepro.2013.11.039

13. Bode, C., Kemmerling, R., & Wagner, S. M. (2013). Internal versus External Supply Chain Risks: A Risk Disclosure Analysis. *Lecture Notes in Logistics*, 109–122. https://doi.org/10.1007/978-3-642-32021-7_6
14. Buchholz, P., & Brandenburg, T. (2018). Demand, Supply, and Price Trends for Mineral Raw Materials Relevant to the Renewable Energy Transition Wind Energy, Solar Photovoltaic Energy, and Energy Storage. *Chemie-Ingenieur-Technik*, *90*(1), 141–153. https://doi.org/10.1002/cite.201700098
15. Busch, J., Dawson, D., & Roelich, K. (2017). Closing the low-carbon material loop using a dynamic whole system approach. *Journal of Cleaner Production*, *149*, 751–761. https://doi.org/10.1016/j.jclepro.2017.02.166
16. Chen, Z., Yang, M., Shi, Q., Kuang, X., Qi, H. J., & Wang, T. (2019). Recycling Waste Circuit Board Efficiently and Environmentally Friendly through Small-Molecule Assisted Dissolution. *Scientific Reports*, Vol. 9. https://doi.org/10.1038/s41598-019-54045-w
17. Coelho, P., Gomes, M., Moreira, C., Oelho, P., Gomes, M., & Moreira, C. (2019). Smart Metering Technology. In A. C. Zambroni de Souza & M. Castilla (Eds.), *Microgrids Design and Implementation* (pp. 97–137). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-98687-6_4
18. Council of Supply Chain Management Professionals. (2013). *SUPPLY CHAIN MANAGEMENT TERMS and GLOSSARY*. Retrieved July 17, 2022, from https://cscmp.org/CSCMP/Educate/SCM_Definitions_and_Glossary_of_Terms.aspx
19. Crispin, G. (2020). The Essence of Risk Identification in Project Risk Management : An Overview. *International Journal of Science and Research (IJSR)*, *9*(2), 1553–1557. https://doi.org/10.21275/SR20215023033
20. Del Giudice, M., Chierici, R., Mazzucchelli, A., & Fiano, F. (2020). Supply chain management in the era of circular economy: the moderating effect of big data. *International Journal of Logistics Management*, *32*(2), 337–356. https://doi.org/10.1108/IJLM-03-2020-0119
21. Delloite. (2012). *Mitigating compliance risk -Implications for global supply chains*. Retrieved July 17, 2022, from https://www2.deloitte.com/us/en/pages/consumer-business/articles/mitigating-compliance-risk-for-global-supply-chain.html
22. Dente, S. M. R., & Hashimoto, S. (2020). COVID-19: A pandemic with positive and negative outcomes on resource and waste flows and stocks. *Resources, Conservation and Recycling*, *161*, 104979. https://doi.org/10.1016/j.resconrec.2020.104979
23. Ding, D., Cooper, R. A., Pasquina, P. F., & Fici-Pasquina, L. (2011). Sensor technology for smart homes. *Maturitas*, *69*(2), 131–136. https://doi.org/10.1016/j.maturitas.2011.03.016
24. Eckelman, M. J., & Chertow, M. R. (2009). Quantifying life cycle environmental benefits from the reuse of industrial materials in pennsylvania. *Environmental*

Science and Technology, *43*(7), 2550–2556. https://doi.org/10.1021/es802345a

25. Ellen MacArthur Foundation. (2013). *Towards the Circular Economy - Economic and Business Rationale for an Accelerated Transition*. Retrieved July 16, 2022, from https://ellenmacarthurfoundation.org/towards-the-circular-economy-vol-1-an-economic-and-business-rationale-for-an
26. Esposito, M., Tse, T., & Soufani, K. (2017). Is the Circular Economy a New Fast-Expanding Market? *Thunderbird International Business Review*, *59*(1), 9–14. https://doi.org/10.1002/tie.21764
27. European Commission. (n.d.-a). *Corporate sustainability reporting*. Retrieved July 17, 2022, from https://finance.ec.europa.eu/capital-markets-union-and-financial-markets/company-reporting-and-auditing/company-reporting/corporate-sustainability-reporting_en
28. European Commission. (n.d.-b). *Critical raw materials*. Retrieved July 17, 2022, from https://ec.europa.eu/growth/sectors/raw-materials/areas-specific-interest/critical-raw-materials_pl
29. European Commission. (2017). *The EU's new Conflict Minerals Regulation: A quick guide if you're involved in the trade in tin, tungsten, tantalum, or gold*. Retrieved July 17, 2022, from https://policy.trade.ec.europa.eu/development-and-sustainability/conflict-minerals-regulation_en
30. European Commission. (2020). *Taxonomy: Final report of the Technical Expert Group on Sustainable Finance*. Retrieved August 23, 2022, from https://ec.europa.eu/info/files/200309-sustainable-finance-teg-final-report-taxonomy_en
31. European Commission. (2021). *Carbon border adjustment mechanism*. Retrieved July 17, 2022, from https://op.europa.eu/en/publication-detail/-/publication/68f4b4b9-0551-11ec-b5d3-01aa75ed71a1/language-en
32. European Commission. (2022a). *Just and sustainable economy: Commission lays down rules for companies to respect human rights and environment in global value chains*. Retrieved July 17, 2022, from https://ec.europa.eu/commission/presscorner/detail/en/IP_22_1145
33. European Commission. (2022b). *Proposal for Ecodesign for Sustainable Products Regulation*. Retrieved August 23, 2022, from https://environment.ec.europa.eu/publications/proposal-ecodesign-sustainable-products-regulation_en
34. European Commission. (n.d.). List of NACE codes. Retrieved July 17, 2022, from https://ec.europa.eu/competition/mergers/cases/index/nace_all.html
35. European External Action Service. (2021). *One year anniversary of the military coup in Myanmar: joint statement*. Retrieved July 17, 2022, from https://www.eeas.europa.eu/eeas/one-year-anniversary-military-coup-myanmar-joint-statement_en
36. European Parliamentary Research Service. (2018). *Circular Economy*. Retrieved July 17, 2022, from

https://www.europarl.europa.eu/thinktank/infographics/circulareconomy/public/index.html

37. Eurostat. (n.d.). *Glossary:Herfindahl Hirschman Index (HHI)*. Retrieved August 23, 2022, from https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Herfindahl_Hirschman_Index_(HHI)
38. Figueira, J., Greco, S., & Ehrogott, M. (2006). Multiple Criteria Decision Analysis State of the Art Surveys. In *International Series in Operations Research & Management Science*. Springer New York, NY. https://doi.org/https://doi.org/10.1007/b100605
39. Frenzel, M., Ketris, M. P., & Gutzmer, J. (2014). On the geological availability of germanium. *Miner Deposita*, *49*, 471–486. https://doi.org/10.1007/s00126-013-0506-z
40. Fu, Y., & Zhu, J. (2019). Big Production Enterprise Supply Chain Endogenous Risk Management Based on Blockchain. *IEEE Access*, *7*, 15310–15319. https://doi.org/10.1109/ACCESS.2019.2895327
41. Gardt, M., Angino, S., Mee, S., & Glöckler, G. (2021). Supply chain disruptions and the effects on the global economy. *ECB Economic Bulletin*, (8).
42. Gaustad, G., Krystofik, M., Bustamante, M., & Badami, K. (2018). Circular economy strategies for mitigating critical material supply issues. *Resources, Conservation and Recycling*, *135*, 24–33. https://doi.org/10.1016/j.resconrec.2017.08.002
43. Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Hultink, E. J. (2017). The Circular Economy – A new sustainability paradigm? *Journal of Cleaner Production*, *143*, 757–768. https://doi.org/10.1016/j.jclepro.2016.12.048
44. Gemechu, E. D., Helbig, C., Sonnemann, G., Thorenz, A., & Tuma, A. (2016). Import-based Indicator for the Geopolitical Supply Risk of Raw Materials in Life Cycle Sustainability Assessments. *Journal of Industrial Ecology*, *20*(1), 154–165. https://doi.org/10.1111/jiec.12279
45. González-Sánchez, R., Settembre-Blundo, D., Ferrari, A. M., & García-Muiña, F. E. (2020). Main dimensions in the building of the circular supply chain: A literature review. *Sustainability (Switzerland)*, *12*(6), 1–25. https://doi.org/10.3390/su12062459
46. Graedel, T. E., Harper, E. M., Nassar, N. T., & Reck, B. K. (2015). On the materials basis of modern society. *Proceedings of the National Academy of Sciences of the United States of America*, *112*(20), 6295–6300. https://doi.org/10.1073/pnas.1312752110
47. Griffin, G., Gaustad, G., & Badami, K. (2019). A framework for firm-level critical material supply management and mitigation. *Resources Policy*, *60*(August 2018), 262–276. https://doi.org/10.1016/j.resourpol.2018.12.008
48. Guan, D., Wang, D., Hallegatte, S., Davis, S. J., Huo, J., Li, S., … Gong, P. (2020). Global supply-chain effects of COVID-19 control measures. *Nature Human Behaviour*, *4*(6), 577–587. https://doi.org/10.1038/s41562-020-0896-8

49. Gunessee, S. (2018). Natural disasters, PC supply chain and corporate performance. *International Journal of Operations & Production Management;, 38*(9), 1796–1814. https://doi.org/10.1108/IJOPM-12-2016-0705
50. Gurtu, A., & Johny, J. (2021). Supply chain risk management: Literature review. *Risks*, *9*(1), 1–16. https://doi.org/10.3390/risks9010016
51. Haldar, S. K. (2020). *Introduction to Mineralogy and Petrology* (2nd ed.). Amsterdam: Elsevier. https://doi.org/10.1016/B978-0-12-820585-3.00001-6.
52. Hayes, A. (2022). *Volatility*. Retrieved July 17, 2022, from https://www.investopedia.com/terms/v/volatility.asp#:~:text=Volatility represents how large an,and standard deviations of returns.
53. Heckmann, I., Comes, T., & Nickel, S. (2015). A critical review on supply chain risk - Definition, measure and modeling. *Omega (United Kingdom)*, *52*, 119–132. https://doi.org/10.1016/j.omega.2014.10.004
54. Hu, Y., & Poustie, M. (2018). Urban mining demonstration bases in China: A new approach to the reclamation of resources. *Waste Management*, *79*, 689–699. https://doi.org/10.1016/j.wasman.2018.08.032
55. International Renewable Energy Agency. (2019). *Global Energy Transformation: A Roadmap to 2050.* Retrieved July 17, 2022, from https://www.irena.org/publications/2019/Apr/Global-energy-transformation-A-roadmap-to-2050-2019Edition
56. Iskraemeco. (2021). *Engage*. Retrieved July 17, 2022, from https://www.iskraemeco.com/en/the-new-edition-of-iskraemecos-magazine-engage-is-here/
57. Ivanov, D., Tsipoulanidis, A., & Schönberger, J. (2019). Supply Chain Risk Management and Resilience. *Global Supply Chain and Operations Management*, (May 2017), 455–479. https://doi.org/10.1007/978-3-319-94313-8_15
58. Joint Research Center. (2022). *The twin green & digital transition: How sustainable digital technologies could enable a carbon-neutral EU by 2050*. Retrieved from https://joint-research-centre.ec.europa.eu/jrc-news/twin-green-digital-transition-how-sustainable-digital-technologies-could-enable-carbon-neutral-eu-2022-06-29_en
59. Kalbar, P. P., Karmakar, S., & Asolekar, S. R. (2012). Selection of an appropriate wastewater treatment technology: A scenario-based multiple-attribute decision-making approach. *Journal of Environmental Management*, *113*, 158–169. https://doi.org/10.1016/j.jenvman.2012.08.025
60. Kalmykova, Y., Sadagopan, M., & Rosado, L. (2018). Circular economy - From review of theories and practices to development of implementation tools. *Resources, Conservation and Recycling*, *135*, 190–201. https://doi.org/10.1016/j.resconrec.2017.10.034
61. Katsaliaki, K., Galetsi, P., & Kumar, S. (2021). Supply chain disruptions and resilience: a major review and future research agenda. *Annals of Operations Research*, 1–38. https://doi.org/10.1007/s10479-020-03912-1

62. Kieckhäfer, K., Breitenstein, A., & Spengler, T. S. (2017). Material flow-based economic assessment of landfill mining processes. *Waste Management*, *60*, 748–764. https://doi.org/10.1016/j.wasman.2016.06.012
63. Knayer, T., & Kryvinska, N. (2022). An analysis of smart meter technologies for efficient energy management in households and organizations. *Energy Reports*, *8*, 4022–4040. https://doi.org/10.1016/j.egyr.2022.03.041
64. Komnitsas, K., & Modis, K. (2006). Soil risk assessment of As and Zn contamination in a coal mining region using geostatisretics. *Science of the Total Environment*, *371*(1–3), 190–196. https://doi.org/10.1016/j.scitotenv.2006.08.047
65. Konisky, D. M., Hughes, L., & Kaylor, C. H. (2016). Extreme weather events and climate change concern. *Climatic Change*, *134*(4), 533–547. https://doi.org/10.1007/s10584-015-1555-3
66. Konitzer, D., Duclos, S., & Rockstroh, T. (2012). Materials for sustainable turbine engine development. *MRS Bulletin*, *37*(4), 383–387. https://doi.org/10.1557/mrs.2012.35
67. Krenev, V. A., Drobot, N. F., & Fomichev, S. V. (2015). Processes for the recovery of bismuth from ores and concentrates. *Theoretical Foundations of Chemical Engineering*, *49*(4), 540–111. https://doi.org/10.1134/S0040579515040132
68. Kromoser, R., Mayer, A., & Kaltenbrunner, A. (2021). *How to navigate a volatile raw materials market*. Retrieved July 16, 2022, from https://www.kearney.com/procurement/article/-/insights/how-to-navigate-a-volatile-raw-materials-market
69. Krook, J., Svensson, N., & Eklund, M. (2012). Landfill mining: A critical review of two decades of research. *Waste Management*, *32*(3), 513–520. https://doi.org/10.1016/j.wasman.2011.10.015
70. Kumar, R., Jagadish, & Ray, A. (2014). *Selection of Material for Optimal Design using Multi-Criteria Decision Making*. *6*, 590–596. https://doi.org/10.1016/j.mspro.2014.07.073
71. Kumar, S. (2006). Environmentally sensitive productivity growth: A global analysis using Malmquist-Luenberger index. *Ecological Economics*, *56*(2), 280–293. https://doi.org/10.1016/j.ecolecon.2005.02.004
72. Leader, A., Gaustad, G., & Babbitt, C. (2019). The effect of critical material prices on the competitiveness of clean energy technologies. *Materials for Renewable and Sustainable Energy*, *8*(2), 1–17. https://doi.org/10.1007/s40243-019-0146-z
73. Li, F. Q., Wang, P., Chen, W., Chen, W. Q., Wen, B. jie, & Dai, T. (2022). Exploring recycling potential of rare, scarce, and scattered metals: Present status and future directions. *Sustainable Production and Consumption*, *30*, 988–1000. https://doi.org/10.1016/j.spc.2022.01.018
74. Li, R., & Leung, G. C. K. (2012). Coal consumption and economic growth in China. *Energy Policy*, *40*(1), 438–443. https://doi.org/10.1016/j.enpol.2011.10.034
75. Lockamy, A. (2019). Benchmarking supplier external risk factors in electronic equipment industry supply chains. *Emerald Insight*, *26*(1), 176–204.

https://doi.org/10.1108/BIJ-01-2018-0004

76. Long, G., Peng, Y., & Bradshaw, D. (2012). A review of copper – arsenic mineral removal from copper concentrates. *Minerals Engineering, 36–38,* 179–186. https://doi.org/10.1016/j.mineng.2012.03.032
77. Lund, S., Manyika, J., Woetzel, J., Barriball, E., Krishnan, M., Alicke, K., … Hutzler, K. (2020). *Risk, resilience, and rebalancing in global value chains*. Retrieved July 16, 2022, from https://www.mckinsey.com/business-functions/operations/our-insights/risk-resilience-and-rebalancing-in-global-value-chains
78. Maguire, B. (2021). *The Twin Transition: How can Green Growth and Digital Transformation go hand in hand to drive Europe's recovery?* Retrieved August 23, 2022, from https://www.euractiv.com/section/digital/video/the-twin-transition-how-can-green-growth-and-digital-transformation-go-hand-in-hand-to-drive-europes-recovery/
79. Markizeti, M., & Heringer, D. (2021). *Fair Meter Report*. Kranj: Iskraemeco d.d.
80. Metheny, M. (2017). *Federal Cloud Computing : The Definitive Guide for Cloud Service Providers* (2nd ed.). Amsterdam: Elsevier. https://doi.org/10.1016/B978-0-12-809710-6.00006-8
81. Moallemi, E. A., Malekpour, S., Hadjikakou, M., Raven, R., Szetey, K., Ningrum, D., … Bryan, B. A. (2020). Achieving the Sustainable Development Goals Requires Transdisciplinary Innovation at the Local Scale. *One Earth*, *3*(3), 300–313. https://doi.org/10.1016/j.oneear.2020.08.006
82. Moats, M., Alagha, L., & Awuah-offei, K. (2021). Towards resilient and sustainable supply of critical elements from the copper supply chain: A review. *Journal of Cleaner Production, 307,* 127207. https://doi.org/10.1016/j.jclepro.2021.127207
83. Murray, A., Skene, K., & Haynes, K. (2017). The Circular Economy: An Interdisciplinary Exploration of the Concept and Application in a Global Context. *Journal of Business Ethics*, *140*(3), 369–380. https://doi.org/10.1007/s10551-015-2693-2
84. Nassar, N. T., Graedel, T. E., & Harper, E. M. (2015). By-product metals are technologically essential but have problematic supply. *Science Advances*, *1*(3), 1–11. https://doi.org/10.1126/sciadv.1400180
85. Nuss, P., & Eckelman, M. J. (2014). Life cycle assessment of metals: A scientific synthesis. *PLoS ONE*, *9*(7), 1–12. https://doi.org/10.1371/journal.pone.0101298
86. Qazi, A., & Akhtar, P. (2020). Computers & Industrial Engineering Risk matrix driven supply chain risk management : Adapting risk matrix based tools to modelling interdependent risks and risk appetite. *Computers & Industrial Engineering*, *139*(August 2018), 105351. https://doi.org/10.1016/j.cie.2018.08.002
87. Rajesh, R., Ravi, V., & Venkata Rao, R. (2015). Selection of risk mitigation strategy in electronic supply chains using grey theory and digraph-matrix approaches. *International Journal of Production Research*, *53*(1), 238–257.

https://doi.org/10.1080/00207543.2014.948579

88. Ramesh, K. ., Sarada, S. P., & Pradeep, K. T. (2020). An integrated framework for the assessment of inbound supply risk and prioritization of the risk drivers: A real-life case on electronics supply chain. *Benchmarking*, *27*(3), 1261–1286. https://doi.org/10.1108/BIJ-03-2019-0119
89. Redlinger, M., & Eggert, R. (2016). Volatility of by-product metal and mineral prices. *Resources Policy*, *47*, 69–77. https://doi.org/10.1016/j.resourpol.2015.12.002
90. Richa, K., Babbitt, C. W., Gaustad, G., & Wang, X. (2014). A future perspective on lithium-ion battery waste flows from electric vehicles. *Resources, Conservation and Recycling*, *83*, 63–76. https://doi.org/10.1016/j.resconrec.2013.11.008
91. Rizos, V., Tuokko, K., & Behrens, A. (2017). *The circular economy, a review of definitions, processes and impacts*. Retrieved July 16, 2022, from https://circulareconomy.europa.eu/platform/en/knowledge/circular-economy-review-definitions-processes-and-impacts
92. Royal Society of Chemistry. (n.d.-a). *Holmium*. Retrieved August 23, 2022, from https://www.rsc.org/periodic-table/element/67/holmium
93. Royal Society of Chemistry. (n.d.-b). *Scandium*. Retrieved August 23, 2022, from https://www.rsc.org/periodic-table/element/21/scandium
94. Ruijters, E., & Stoelinga, M. (2015). Fault tree analysis : A survey of the state-of-the-art in modeling , analysis and tools. *Computer Science Review*, *15–16*, 29–62. https://doi.org/10.1016/j.cosrev.2015.03.001
95. Saevarsdottir, G., Kvande, H., & Magnusson, T. (2021). Greenhouse gas emissions from silicon production - development of carbon footprint with changing energy systems. *Proceedings of the 16th International Ferro-Alloys Congress (INFACON XVI) 2021*. Retrieved from https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3926088
96. Santillán-Saldivar, J., Cimprich, A., Shaikh, N., Laratte, B., Young, S. B., & Sonnemann, G. (2021). How recycling mitigates supply risks of critical raw materials: Extension of the geopolitical supply risk methodology applied to information and communication technologies in the European Union. *Resources, Conservation and Recycling*, *164*, 105108. https://doi.org/10.1016/j.resconrec.2020.105108
97. Scott, G. (2021). *Understanding Component and Parts Shortages (and How to Survive Them).* Retrieved July 17, 2022, from https://www.jabil.com/blog/understanding-component-supply-shortages.html
98. Sillanpää, M., & Ncibi, C. (2017). *A Sustainable Bioeconomy* (1st ed.). Cham: Springer. https://doi.org/https://doi.org/10.1007/978-3-319-55637-6_1
99. Sillanpää, M., & Ncibi, M. C. (2019). *The Circular Economy: Case Studies about the Transition from the Linear Economy*. Amsterdam: Elsevier.
100. Statista. (n.d.-a). *Praseodymium oxide price globally 2030*. Retrieved July 18, 2022, from https://www-statista-com.nukweb.nuk.uni-lj.si/statistics/450148/global-

reo-praseodymium-oxide-price-forecast/

101. Statista. (n.d.-b). *Rare earth oxide gadolinium oxide price globally 2009-2025*. Retrieved July 18, 2022, from https://www-statista-com.nukweb.nuk.uni-lj.si/statistics/450160/global-reo-gadolinium-oxide-price-forecast/
102. Statista. (n.d.-c). *Samarium oxide price 2009-2030*. Retrieved July 18, 2022, from https://www-statista-com.nukweb.nuk.uni-lj.si/statistics/450155/global-reo-samarium-oxide-price-forecast/
103. Sverdrup, H. U., Ragnarsdottir, K. V., & Koca, D. (2017). An assessment of metal supply sustainability as an input to policy : security of supply extraction rates, stocks-in-use , recycling, and risk of scarcity. *Journal of Cleaner Production*, *140*, 359–372. https://doi.org/10.1016/j.jclepro.2015.06.085
104. Trkman, P., & McCormack, K. (2009). Supply chain risk in turbulent environments-A conceptual model for managing supply chain network risk. *International Journal of Production Economics*, *119*(2), 247–258. https://doi.org/10.1016/j.ijpe.2009.03.002
105. Tsoulfas, G. T., & Pappis, C. P. (2006). Environmental principles applicable to supply chains design and operation. *Journal of Cleaner Production*, *14*(18), 1593–1602. https://doi.org/10.1016/j.jclepro.2005.05.021
106. U.S. Geological Survey. (2022). *Mineral Commodity Summaries*. Retrieved July 16, 2022, from https://pubs.er.usgs.gov/publication/mcs2022
107. Vakil, B., & Linton, T. (2021). *Why We're in the Midst of a Global Semiconductor Shortage*. Retrieved July 17, 2022, from https://hbr.org/2021/02/why-were-in-the-midst-of-a-global-semiconductor-shortage
108. Watari, T., Nansai, K., & Nakajima, K. (2020). Review of critical metal dynamics to 2050 for 48 elements. *Resources, Conservation and Recycling*, *155*. https://doi.org/10.1016/j.resconrec.2019.104669
109. Watson, G. V. R., & Powrie, W. (2013). Landfill as a Resource. In *Waste as a Resource* (pp. 205–226). Cambridge: Royal Society of Chemistry. https://doi.org/https://doi.org/10.1039/9781849737883
110. World Bank. (n.d.). *Political stability and absence of violence/terrorism*. Retrieved July 17, 2022, from https://tcdata360.worldbank.org/indicators/b89c1cd1?country=BRA&indicator=40270&viz=line_chart&years=2013,2018
111. World Bank. (2022). *Solid Waste Management*. Retrieved July 17, 2022, from https://www.worldbank.org/en/topic/urbandevelopment/brief/solid-waste-management
112. Yang, W. Bin, Yuan, C. S., Chen, W. H., Yang, Y. H., & Hung, C. H. (2017). Diurnal variation of greenhouse gas emission from petrochemical wastewater treatment processes using in-situ continuous monitoring system and the associated effect on emission factor estimation. *Aerosol and Air Quality Research*, *17*(10), 2608–2623. https://doi.org/10.4209/aaqr.2017.08.0276
113. Young, S. B. (2018). Responsible sourcing of metals: certification approaches for

conflict minerals and conflict-free metals. *International Journal of Life Cycle Assessment*, *23*(7), 1429–1447. https://doi.org/10.1007/s11367-015-0932-5

114. Zwiler, F., & Herm, M. (2012). Supply Chain Risk Management in the Electronics Industry. In J. Emblemsvåg (Ed.), *Risk Management for the Future: Theory and Cases* (pp. 468–496). Rijeka: IntechOpen. https://doi.org/10.5772/32958

APPENDICES

Appendix 1: Povzetek (Summary in Slovene Language)

Organizacije, ki upravljajo elektronske komponente, se soočajo z nizi pomanjkanj, višanja cen in podaljševanja dobavnih rokov. Ko je spomladi leta 2020 izbruhnila epidemija Covid-19, se je pomanjkanje še pospešilo, povečala pa se je tudi negotovost. Zaradi globalizacije imajo geopolitična vprašanja pomembno vlogo pri motnjah dobavnih verig. Hkrati pa globalno segrevanje in podnebne spremembe predstavljajo skrb za prihodnost. Čeprav trend segrevanja traja že dlje časa, se je njegova hitrost v zadnjih sto letih močno povečala zaradi izgorevanja fosilnih goriv. Z naraščanjem števila prebivalcev se povečuje tudi količina porabljenih fosilnih goriv. Po oceni Mednarodne agencije za obnovljivo energijo je potrebno, da bi izpolnili podnebne cilje, z energijo povezane emisije ogljikovega dioksida do leta 2050 zmanjšati za 70 % v primerjavi z današnjimi ravnmi. Trenutno je na voljo nova zelena tehnologija za pomoč pri reševanju tega problema. Obnovljivi viri energije, kot sta sonce in veter, lahko leta 2050 zadovoljijo 86 % potreb po električni energiji. Upravljanje povpraševanja po energiji je lahko učinkovita strategija za zmanjšanje porabe energije, zato se pametno merjenje energije dojema kot ključni dejavnik energetskega prehoda, hkrati pa kot gonilo digitalizacije in energetske učinkovitosti. Pametni števci so izdelki, ki so odvisni od elektronskih komponent in zato nanje neposredno vplivajo motnje v dobavni verigi elektronskih komponent in materialov, ki se uporabljajo za njihovo izdelavo.

Za obvladovanje tveganja morajo podjetja skrbno načrtovati svoje strategije pridobivanja virov. Namen magistrske naloge je raziskati in preslikati tveganja, povezana s komponentami pametnega števca, pridobiti pregled, katera področja so najbolj kritična in kaj je možno storiti, da bi se spopadli z morebitnimi motnjami v dobavnih verigah v prihodnosti. Magistrsko delo je sestavljeno iz treh delov, ki so opisani v nadaljevanju.

Prvi del je teoretični pregled obvladovanja tveganj v oskrbovalni verigi. Predstavili smo kako poteka proces obvladovanja tveganj in posebnosti oskrbovalnih verig v elektronski industriji. Narejen je bil podroben pregled kritičnih in konfliktnih materialov, pri čemer smo se posebej osredotočili na vplive na okolje, prihajajoče spremembe zakonodaje in tudi na priložnosti, povezane s temi materiali. Industrijo pametnih števcev smo predstavili bolj konkretno. Razložen je koncept krožnega gospodarstva in opredeljene so trajnostne aktivnosti, ki jih je mogoče izvajati za doseganje krožnega gospodarstva. Po pregledu literature je bila sprejeta odločitev, da se osredotočimo na prvi korak dobavne verige, to je na surovine. Za analizo tveganja, povezanega z izbrano surovino, smo uporabili metodo večkriterijske odločitvene analize TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution).

Drugi del je namenjen zbiranju in strukturiranju uporabljenih podatkov in implementaciji metode za identifikacijo tveganj in izračun ocene tveganja za posamezne materiale v šestih različnih scenarijih. Uporabljeni so bili obstoječi parametri in indeksi, kot so globalne rezerve, tržna koncentracija, nestanovitnost cen, letna rudarska proizvodnja, potencial globalnega segrevanja, povpraševanje po mineralnih virih, kumulativno povpraševanje po energiji itd.

Tretji del je sestavljen iz analize rezultatov in raziskovanja, kako se trajnostne strategije za ublažitev tveganj v dobavni verigi - kot so recikliranje, ponovna uporaba, urbano rudarjenje - že izvajajo in kakšen je njihov potencial v prihodnosti. V tem delu smo ocene tveganja za surove materiale, izračunane v drugem delu naloge, povezali s komponentami konkretnega pametnega števca.

Rezultati so pokazali, da imajo platinske kovine, natančneje rodij, platina, paladij in zlato visoko tveganje v osnovnem scenariju. K temu pripomorejo majhne svetovne rezerve, nizka koncentracija rude in dejstvo, da se v veliki meri proizvajajo kot stranski produkt. Gledano s socialnega vidika so tveganja izjemno visoka za kobalt, sledijo mu tantal, galij in nekatere redke zemlje. Pri scenariju, kjer je poudarek na oskrbi pa so najbolj prizadeti galij, germanij, grafit, indij, telur in redke zemlje. Recikliranje lahko ublaži tveganje oskrbe, geopolitično tveganje in socialna tveganja, medtem ko lahko urbano in odlagališčno rudarjenje pomaga zmanjšati okoljska tveganja. Strategija ponovne uporabe in uporaba stranskih proizvodov, ki se trenutno zavržejo, lahko pomagata ublažiti tveganje fizične nedostopnosti in in neizpolnjevanje povpraševanja po materialih. V nalogi izdelani zemljevid tveganj in predlagane trajnostne strategije za ublažitev tega tveganja so pokazatelj, v katero smer bi bilo potrebno usmeriti nadaljnje raziskave iz tega področja. To bi nam pomagalo najti aktivnosti, ki bi nam omogočile, da bi se s krizo spopadli s čim manjšimi posledicami.

Appendix 2: Data for Demand Risk Metrics

Symbol	Annual Mine Production (metric tons)	Electronics Sector Consumption in EU (%)	Price ($ per kg)	Price Volatility (5-year period)
Al	68,000,000	42%	3.1	0.16
Cu	21,000,000	80%	9.3	0.10
Fe	1,900,000,000	47%	0.1	0.06
Mg	950,000	66%	5.5	0.43
Ni	2,700,000	51%	18.3	0.18
Ti	210,000	13%	11.7	0.04
Zn	13,000,000	84%	3	0.10
Au	3,000	11%	57871.3	0.16
Pd	200	91%	83591	0.40
Pt	180	78%	38580	0.13
Rh	180	85%	771617	1.00
Ag	24,000	41%	803.8	0.18
Sb	110,000	46%	11.5	0.23
Ba	7,300,000	0%	0.2	0.01
Be	260	97%	610	0.03
Bi	19,000	10%	8.05	0.22
Co	170,000	60%	48.5	0.32
Ga	430	100%	570	0.08
Ge	140	100%	1200	0.14
Gr	1,000,000	68%	1.8	0.06
Hf	1,200	78%	830	0.06
In	920	95%	220	0.20
Li	100,000	10%	18.7	0.24
Mn	20,000,000	54%	0.0052	0.15
Nb	75,000	53%	20	0.05
P	220,000,000	6%	0.0827	0.04
Si	8,500,000	46%	3.086	0.14
Ta	2,100	80%	158	0.13
Te	580	70%	68	0.21
Sn	300,000	91%	33.1	0.26
W	79,000	11%	0.27	0.10
V	110,000	96%	18.1	0.35
Ce	110,416	18%	2	0.00
Dy	2,553	100%	400	0.31
Eu	919	100%	31	0.39
Gd	4,987	93%	19.7	0.25
La	75,454	30%	2	0.00
Nd	46,960	71%	49	0.04
Pr	13,822	63%	45.7	0.31
Sm	6,411	100%	1.75	0.99
Tb	714	100%	1300	0.46
Y	17,764	58%	38	0.28
Cd	24,000	80%	2.5	0.16
Cr	41,000,000	77%	7.5	0.16
Pb	4,300,000	92%	2.4	0.08
As	59,000	76%	1.28	0.14
Mo	300,000	73%	36	0.25
S	80,000,000	4%	0.0992	0.41

Appendix 3: Data for Supply Risk Metrics

Symbol	Global Reserves (metric tons)	Ore Concentration (%)	Static Index of Depletion (years)	Production % as byproduct	EOL-RIR (%)
Al	32,000,000,000	50%	471	0%	12%
Cu	880,000,000	3%	42	9%	17%
Fe	180,000,000,000	55%	95	1%	31%
Mg	7,200,000,000	40%	7579	5%	13%
Ni	95,000,000	1%	35	2%	17%
Ti	750,000,000	35%	3571	100%	19%
Zn	250,000,000	6%	19	10%	31%
Au	54,000	0.0003%	18	14%	29%
Pd	70,000	0.0005%	350	97%	28%
Pt	70,000	0.0005%	389	16%	25%
Rh	70,000	0.001%	389	100%	28%
Ag	530,000	0.005%	22	71%	19%
Sb	2,000,000	5%	18	80%	28%
Ba	389,000	33%	0	2%	1%
Be	100,000	4%	385	11%	0%
Bi	81,000,000	0.06%	4263	90%	0%
Co	7,600,000	5%	45	85%	22%
Ga	100,000	0.01%	233	100%	0%
Ge	24,000	0.001%	171	100%	2%
Gr	320,000,000	75%	320	0%	3%
Hf	70,000,000	0.15%	58333	100%	0%
In	25,000	0.01%	27	100%	0%
Li	22,000,000	1%	220	52%	0%
Mn	1,500,000,000	55%	75	3%	8%
Nb	17,000,000	5%	227	2%	0%
P	71,000,000,000	20%	323	0%	0%
Si	605,000,000,000	46%	71176	0%	0%
Ta	139,000	69%	66	28%	0%
Te	31,000	0.001%	53	100%	1%
Sn	4,900,000	8%	16	3%	31%
W	3,700,000	3%	47	5%	42%
V	24,000,000	5%	218	82%	2%
Ce	60,000,000	3%	543	73%	1%
Dy	1,200,000	0.06%	470	100%	0%
Eu	240,000	0.01%	261	100%	38%
Gd	480,000	0.02%	96	100%	1%
La	32,400,000	2%	429	93%	1%
Nd	18,000,000	1%	383	100%	1%
Pr	6,000,000	0.3%	434	100%	10%
Sm	1,320,000	0.07%	206	82%	1%
Tb	120,000	0.01%	168	100%	6%
Y	600,000	0.03%	34	29%	31%
Cd	600,000	0.03%	25	100%	30%
Cr	570,000,000	55%	14	2%	21%
Pb	90,000,000	3%	21	10%	75%
As	1,180,000	51%	20	92%	0%
Mo	16,000,000	8%	53	46%	30%
S	605,000,000,000	35%	7563	0%	5%

Appendix 4: Socio-Political Risk Metrics

Symbol	Geographical Concentration of Production (HHI)	Socio-Political weighted HHI (WGI PSAV-HHI)	Social Hotspots (per $ of material produced)	Net Import Reliance: EU Perspective (%)
Al	3596	-1664	116	59%
Cu	1272	145	166	44%
Fe	3528	-1706	126	72%
Mg	7149	-3595	150	100%
Ni	2018	-822	146	28%
Ti	3776	-1518	138	100%
Zn	1663	-502	98	60%
Au	909	-45	93	
Pd	3133	-1311	94	93%
Pt	3133	-1311	94	98%
Rh	3133	-1311	94	100%
Ag	1250	-522	95	40%
Sb	3652	-2063	149	100%
Ba	2282	-1321	164	70%
Be	5010	1340	83	0%
Bi	7159	-3516	167	50%
Co	5058	-11469	664	86%
Ga	9542	-4771	154	31%
Ge	5434	-2314	111	31%
Gr	6799	-3402	153	98%
Hf	1989	884	76	0%
In	3897	-1471	110	0%
Li	3940	3272	75	100%
Mn	2058	137	211	90%
Nb	7845	-2981	55	100%
P	1992	-862	123	100%
Si	5092	-2513	134	63%
Ta	1972	-3085	435	99%
Te	3858	-1562	118	0%
Sn	1801	-887	251	0%
W	7032	-3490	152	11%
V	4808	-2492	135	47%
Ce	3995	-1749	164	100%
Dy	3995	-1749	164	100%
Eu	3995	-1749	164	100%
Gd	3995	-1749	164	100%
La	3995	-1749	164	100%
Nd	3995	-1749	164	100%
Pr	3995	-1749	164	100%
Sm	3995	-1749	164	100%
Tb	3995	-1749	164	100%
Y	3995	-1749	164	100%
Cd	2117	-712	109	0%
Cr	2695	-798	87	66%
Pb	2514	-1015	116	15%
As	3893	-1287	126	32%
Mo	2582	-748	111	100%
S	926	-227	98	0%

Appendix 5: Data for Environmental Risk Metrics

Symbol	Global Warming Potential (kgCO2eq)	Cumulative Energy Demand (MJ eq/ kg)	Freshwater Eutrophication (kg P-eq / kg)	Human Toxicity(Cancer and Non-Cancer) (CTUh/kg) USEtox 1.02 Reccomended + Interim	Terrestrial Acidification (kg SO2 - eq / kg)
Al	20	222	0.0037	0.0000054	0.034
Cu	4	61	0.13	0.00027	0.39
Fe	5	69	0.00073	0.00000041	0.0052
Mg	32	401	0.00019	0.0000012	0.0023
Ni	12	177	0.028	0.000023	1.5
Ti	31	437	0.0021	0.0000027	0.036
Zn	5	62	0.0051	0.000059	0.039
Au	17,083	256403	230	0.39	120
Pd	6,117	84645	10	0.018	1700
Pt	29,145	368365	51	0.092	2200
Rh	26,849	344844	150	0.27	5200
Ag	360	5492	3.6	0.0069	8.5
Sb	10	149	0.24	0.00042	0.22
Ba	0	5	0.00018	0.000000083	0.00082
Be	122	1720	0.031	0.000021	0.52
Bi	59	697	0.022	0.000017	0.38
Co	10	137	0.004	0.0000038	0.089
Ga	195	2738	0.061	0.00005	0.45
Ge	170	2890	0.26	0.0029	1.9
Gr	2	55			
Hf	131	3510	0.071	0.000048	0.77
In	223	2715	0.15	0.0017	1.2
Li	168	2514	0.0061	0.0000037	0.038
Mn	4	62	0.00067	0.00000033	0.0094
Nb	13	172	0.0037	0.0000064	0.053
P					
Si					
Ta	305	4749	0.15	0.00012	1.7
Te	8	135	0.89	0.0018	2.5
Sn	22	327	0.012	0.0000081	0.43
W	13	133	0.0000093	0.000034	0.29
V	33	516	0.00000043	4.4E-09	0.14
Ce	76	252	0.005	0.0000061	0.055
Dy	107	1170	0.023	0.000028	0.25
Eu	103	7750	0.15	0.00019	1.7
Gd	111	914	0.018	0.000022	0.2
La	75	215	0.0043	0.0000052	0.047
Nd	74	344	0.0068	0.0000083	0.075
Pr	73	376	0.0075	0.0000091	0.081
Sm	106	1160	0.023	0.000028	0.25
Tb	108	5820	0.12	0.00014	1.3
Y	15	295	0.0059	0.0000071	0.064
Cd	1	17	0.0027	0.000014	0.022
Cr	31	538	0.0011	0.000031	0.017
Pb	1	17	0.0022	0.0000099	0.028
As	0	5	0.0092	0.000035	0.0082
Mo	6	117	0.54	0.0009	0.16
S					

Appendix 6: Country level data on social hotspots score (Social hotspots score per dollar of material produced)

Countries	Social Hotspots Score	Countries	Social Hotspots Score	Countries	Social Hotspots Score
Argentina	407	Indonesia	276	Philippines	118
Australia	22	Iran	102	Poland	33
Bahrain	42	Ireland	18	Portugal	29
Belgium	44	Israel	40	Russia	136
Bolivia	145	Japan	35	Rwanda	109
Brazil	58	Kazakhstan	206	South Africa	55
Bulgaria	69	Korea	56	Sri Lanka	97
Burundi	154	Kyrgystan	383	Sweden	23
Canada	38	Laos	530	Taiwan	48
Chile	45	Madagascar	125	Tajikistan	222
China	156	Malaysia	126	Thailand	145
Colombia	181	Mexico	97	Turkey	61
Congo	889	Morocco	149	Uganda	356
Cuba	685	Mozambique	185	Ukraine	253
Ethiopia	356	Myanmar	575	United Arab Emirates	28
France	24	Netherlands	28	United Kingdom	37
Gabon	729	New Caledonia	37	United States	38
Germany	29	Nigeria	653	Uzbekistan	222
Ghana	277	Norway	76	Vietnam	229
Guatemala	258	Pakistan	328	Zambia	648
Iceland	32	Papua New Guinea	37	Zimbabwe	241
India	215	Peru	96		