Assessing Supply Disruption Impacts along the Supply Chain within Life Cycle Sustainability Assessment – a novel approach applied to the Swiss Economy

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Abstract

The Swiss service-oriented economy is as many other Western economies almost exclusively dependent on the supply of materials and products from abroad and related supply chains often involve several actors around the world. The supply chains for technologies used in the Swiss mobility, energy provision and storage as well as ICT sectors, three key sectors with a high economic and strategic importance for the Swiss economy, are particularly complex. Due to their complexity, these supply chains may be affected by supply disruption events occurring anywhere around the world. Just recently, significant disruptions in the supply chains of these three sectors have for example been caused by the COVID-19 pandemic, the Brexit and the China-United States trade war.

To build more resilient supply chains, it is key to anticipate and manage supply risks and to implement technologies associated with comparably low supply risks. A common way to identify such supply risks is the evaluation of supply disruption impacts with criticality assessment approaches. Some of these approaches have been integrated into the Life Cycle Sustainability Assessment (LCSA) framework to, amongst other benefits, allow for assessing the socio-economic impacts of supply disruptions and environmental, economic and social impacts with the same approach and thus for avoiding burden-shifting between these two types of impacts. Key limitations of the existing approaches assessing criticality within LCSA are however that they do not allow for evaluating supply disruption impacts along the entire supply chain as well as for addressing different time horizons. This dissertation thus aims to address this research gap with the development of the SPOTTER approach.

The objective of the SPOTTER approach is to provide a quantitative assessment of supply disruption impacts along the full supply chain in the short-term (i.e. the next 5 years) and medium-term (i.e. in 5 to 15 years) that allows for identifying the most relevant supply risks within global supply chains and over different time horizons. To this end, it analyzes supply disruption hotspots (i.e. relatively highest impacts along the supply chain) and determines overall supply disruption impacts (i.e. the total impact for the supply chain) over the two time horizons. The hotspots and overall impacts caused by global and country-specific supply disruption events are thereby assessed and aggregated into the two categories *cost variability* and *limited availability*. Considered events comprise six short-term events *geopolitical instability*, *child labor restrictions*, *trade barriers*, *depletion of economic resources*, *price volatility* and *limited recyclability* as well as four medium-term events *demand growth*, *co-product dependency*, *primary raw material reliance* and *depletion of ultimate resources*. Scores of the overall impacts and hotspots are calculated by multiplying amounts of inventory flows (i.e. material/product flows between different

country-specific supply chain processes) with respective characterization factors (CFs) that define supply disruption impacts on the product system. These CFs are case-specific and are defined based on supply disruption probability and vulnerability indicators. This dissertation has provided an overview and has explained the rationale of the SPOTTER approach by illustrating the selection and use of the indicators defining the CFs and by presenting how the scores of overall impacts and hotspots are calculated. Given the challenges regarding data availability for assessments along the supply chain, a procedure for the practical application of the SPOTTER approach has additionally been presented. This procedure, here called the 'SPOTTER implementation procedure' involves guidelines for scope definition, inventory analysis, screening of inventory flow relevance and impact assessment.

After the method development, the application of the SPOTTER approach has been demonstrated in a first case study, where the hotspots of supply disruptions in the short-term have been analyzed along the cobalt and aluminium supply chains of electric vehicles (EVs) used in Switzerland by following the 'SPOTTER implementation procedure'. Based on this case study, data sources suitable for an assessment with the SPOTTER approach have been identified as well as the quantification of the inventory flows along the supply chain, the calculation of impact scores and the interpretation of results from the hotspot analysis have been explained. The location of the identified hotspots have been presented on global maps and the magnitude of the hotspots in relation to the overall impacts have been illustrated with pie charts and stacked bar charts. The hotspots with the relatively highest magnitudes suggest, on the one hand, potential disruptions of cobalt ore supply from the Congo to Australia and Canada, EV supply from the USA to Switzerland, EV wiring supply from Mexico to the USA and Al wire supply from Bahrain to Morocco. On the other hand, these hotspots indicate potential supply disruptions in the global markets of traction batteries and EV components used in the USA, cobalt powder and battery components used in China and South Korea, cobalt ore used in Australia and EVs used in Switzerland. Furthermore, the results of the hotspot analysis have been compared with the results of existing studies. This comparison has shown that some results such as the indication of an unstable cobalt supply are in line with the outcomes of existing studies but also that our study provides new country-specific information about relevant supply risks along the full supply chain.

To determine bottlenecks in the supply chains of infrastructure and fuels used in the Swiss mobility, energy and ICT sectors and to identify technologies associated with comparably low supply risks used in these three sectors, a second case study has been performed. In this case study, supply disruption hotspots have been analyzed and the impacts of different technologies have been compared. Considering the tremendous efforts regarding data acquisition and computation for such an assessment on a sectoral level, a screening procedure that allows for identifying the most influential inventory flows for an assessment with the SPOTTER approach has been introduced. This procedure is executed as an integral part of the goal and scope definition and inventory analysis within the SPOTTER approach. It has then been demonstrated how to apply the screening procedure in combination with the 'SPOTTER implementation procedure' for the hotspot analysis and impact comparisons performed in this case study. Results of the hotspot analysis regarding the supply of infrastructure have been presented for each sector individually and for the combination of the three sectors. These results suggest that supply disruptions may occur especially along supply chains of solar panels, nuclear power plant equipment, lithium-ion batteries and electronic devices, which describe key technologies for the Swiss economy. In particular, relatively high impacts have been identified related to the supply of cobalt, natural graphite, gallium, hafnium, battery cells, mobile phones, laptops and flat-screen monitors from African or Asian countries as well as related to the supply of solar panels, hafnium powder and natural graphite from the global market. The results of the hotspot analysis regarding the fuel supply, which have been presented for the combination of all three sectors, indicate high risks for the supply of natural gas, coal, uranium and petroleum oil from Russia, Niger and Nigeria as well as potential supply disruptions in the global market of coal, uranium and fuel wood. The results of the impact comparisons suggest that the utilization of some key technologies used within the different sectors is associated with a relatively lower supply risk. For example, lower overall impacts have been assessed for the implementation of wind turbines compared to solar panels and the supply of German laptops compared to Chinese laptops. With regard to the mobility sector, the comparison between battery electric cars and conventional cars indicates that the utilization of battery electric cars has higher risks for the supply of infrastructure but lower risks for the supply of fuels. Additionally, the results of the performed hotspot analysis and impact comparisons have been compared with the results of existing studies. This comparison has shown that our study provides besides some already presented results in the literature such as the hotspots of cobalt or the comparably higher impacts for the infrastructure used in battery electric vehicles also new and more comprehensive information about relevant supply risks within global supply chains for different sectors of an economy.

The information on supply risks provided with the two case studies has finally been considered for suggesting suitable risk mitigation measures targeted toward policy-makers in Switzerland as well as Swiss companies and retailers. It has thus been demonstrated that our case studies with the SPOTTER approach provide so-far missing information that is relevant for the identification of pertinent risk mitigation measures.

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List of abbreviations

Al	Aluminum
BEC	Battery electric car
BEV	Battery electric vehicle
Cell	Lithium-ion battery cell
CF	Characterization factor
Co	Cobalt
Congo	The Democratic Republic of the Congo
DI	Indicator for diversity of supply
EI	Indicator for supply disruption event
EoL	End-of-life
EoL-RR	End-of-life recycling rate
EU	European Union
EV	Electric vehicle
EVI	Indicator for economic importance or economic damage
FU	Functional unit
GHG	Greenhouse gas
GI	Geopolitical instability
HHI	Herfindahl-Hirschman Index
HS code	Harmonized System code
ICT	Information and Communication Technology
ICEC	Internal combustion engine car
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCSA	Life Cycle Sustainability Assessment
LIB	Lithium-ion battery
MT	Medium-term
PGMs	Platinum Group Metals
PHEV	Plug-in hybrid electric vehicle
PI	Indicator for supply disruption probability
PVI	Indicator for vulnerability to physical shortage

SLCA	Social Life Cycle Assessment
SME	Small and medium-sized enterprises
ST	Short-term
USA	United States of America
USGS	U.S. Geological Survey
WGI	Worldwide Governance Indicator
WGI(PS)	Worldwide Governance Indicator – Political Stability and Absence of Violence/Terrorism

"Two basic rules of life are: 1) Change is inevitable. 2) Everybody resists change."
~ W. Edwards Deming

1. Introduction

1.1 Motivation

Our society uses various products for example to satisfy its basic needs, to construct housing and infrastructure as well as to provide services related to mobility, heating, lighting, communication, healthcare and entertainment. The supply of these products involves a sequence of production and distribution processes. Such a sequence of processes is called the supply chain of a product (Kortus-Schultes and Ferfer 2005). Processes along a supply chain are for example the extraction of minerals from natural resource stocks, the processing and refining of these minerals into raw materials, the fabrication of intermediate products out of these raw materials and the manufacturing of final products (Chen and Graedel 2012; Dewulf et al. 2015a).

Nowadays, supply chains are often complex because they involve several actors in different parts of the world (Gurzawska 2020). One reason for such a supply chain complexity is the globalization, which has led to a specialization of production processes in countries where business activities are most profitable (Hanson 2001). A prominent example is the outsourcing of textile and clothing production to Asia in order to lower production costs (El Achkar Hilal et al. 2022). Another reason is the increasing use of natural resources from remote places in the world. An example is the increasing use of oil and gas extracted in the United States, Russia and Saudi Arabia in the mobility and energy generation sectors (Enerdata 2022b, a). A third reason is that a higher number of raw materials are today required for the production of products. Figure 1 illustrates the increase in the variety of raw materials that have been used for the provision of mobility services and energy supply.

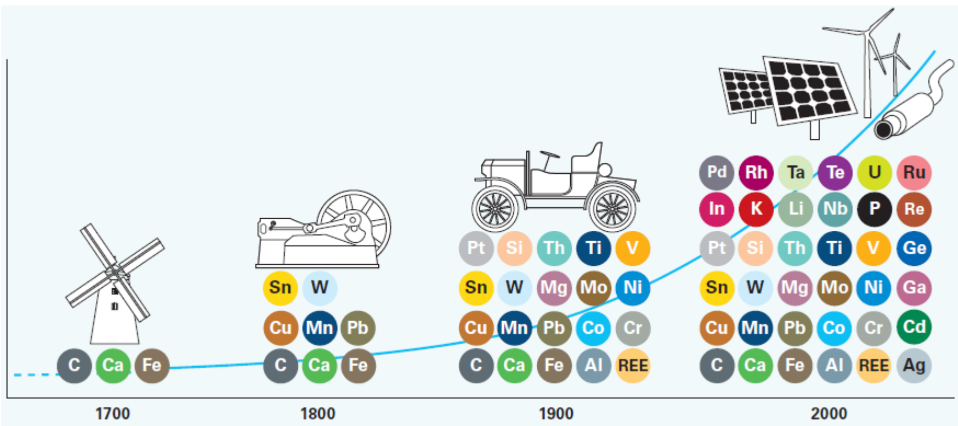

Figure 1: Development of the raw material intensity of products over time
considering raw materials used in products within the mobility and energy sectors since the year 1700. Figure created by Zepf et al. (2014).

The performance of supply chains depends on various conditions including for example consumer preferences, transport and production infrastructures, policies and regulations as well as the state of the natural environment. Changes in these external socio-economic and environmental conditions potentially affect this performance and result, in extreme cases, in disruptions of the supply chain (Dewulf et al. 2016; Porter and Kramer 2006). Complex supply chains are naturally more likely to be affected/disrupted because, as highlighted by Nuss et al. (2016) and Ku et al. (2018), events that lead to such changes may occur anywhere along the supply chain. According to Schrijvers et al. (2020b), the effects of such events are generally a decrease in supply or a change in demand, which can also be observed in a variety of recent events. As one example, the COVID-19 pandemic has led to broken transportation and distribution networks, surges in demand for healthcare products and essential food items as well as decreases in demand for automobile and textile products (Kumar et al. 2020). As another example, the China-United States trade war has resulted in supply shocks through increased tariffs on goods traded between China and the United States of America (USA) (Bekkers and Schroeter 2020). As a third example, natural disasters and the Russian-Ukrainian conflict have been responsible for a decline in food supply (Jagtap et al. 2022; Reddy et al. 2016).

Continuously operating businesses are an indication of the economic stability of a country (Schrijvers et al. 2020a). In order to ensure such businesses, resilient supply chains, i.e. supply chains that can "anticipate", "adapt" and "respond" to supply disruptions and that eventually become more robust (Ali et al. 2017; Christopher and Peck 2004; Ponomarov and Holcomb 2009), need to be created. In view of a sustainable economy, resilient supply chains are particularly required for products that are strategically relevant to a country. In this context, the European Green Deal (European Commission 2019) and the new Industrial Strategy of the European Union (EU) (European Commission 2020a) have emphasized the importance of resilient supply chains to foster a sustainable transformation of the European economy.

The countries of the EU are among the 196 countries that have signed the Paris Agreement (UNFCCC 2015) and thus declared to reach net zero by 2050. To achieve this goal, implementing products and services that facilitate a reduction of greenhouse gas (GHG) emissions is particularly important. Examples of such products, also sometimes called clean technologies (Alonso et al. 2012; Eggert 2017; Habib and Wenzel 2014), are solar panels and wind turbines, as they allow for a reduction of carbon emissions in the energy generation process (IPCC 2014), as well as electric vehicles, which promise the potential for reduced carbon emissions of mobility services (Hirschberg et al. 2016; Lattanzio 2020).

But reaching resiliency, especially in the supply chains for clean and innovative technologies, is expected to be challenging as a prediction of supply disruptions is often difficult or even impossible (Sprecher et al. 2017a). The shutdown of entire production facilities for traction batteries, solar panels and wind turbines caused by the COVID-19 pandemic (Dong et al. 2022; Dyatkin and Meng 2020) has just recently demonstrated that global supply chains for these technologies can rather easily be affected by severe supply disruptions. The occurrence of such supply disruptions is also expected in the coming years because key technologies are often dependent on a large variety of so-called critical raw materials (IEA 2021). Some raw materials are rated as "critical", as they are economically important and the risk for a disruption of their supply is considered to be high (Ferro and Bonollo 2019).

To better anticipate such supply disruptions and thus facilitate the establishment of resilient supply chains, governmental entities and/or research organizations have started to analyze the criticality of raw materials used in key technologies for their specific country/region and provided lists of critical raw materials. Examples of resulting lists of critical raw materials that have been established for the EU, the United States of America, Australia, Japan and the Republic of Korea are summarized in Figure 2.

Latest list of critical raw materials for different countries/regions

√: European Union; √: United States; √: Australia; √: Japan; √: Republic of Korea

Material	European Union	United States	Australia	Japan	Republic of Korea
Antimony	√	√	√	√	√
Arsenic		√			√
Barium/Barite	√	√			√
Bauxite/ Aluminium	√	√	√		
Beryllium	√	√	√	√	√
Bismuth	√	√	√		√
Boron/Borate	√				√
Cadmium					√
Carbon				√	
Cesium		√			√
Chromium		√	√	√	√
Cobalt	√	√	√	√	√
Copper				√	
Coking Coal	√				
Fluorspar/ Fluorine		√		√	
Gallium	√	√	√	√	√
Germanium	√	√	√	√	√
Gold				√	
Hafnium	√	√	√		√
Helium		√	√		
REEs*	√	√	√	√	√
Indium	√	√	√	√	√
Lead				√	
Lithium	√	√	√	√	√
Magnesium	√	√	√	√	√
Manganese		√	√	√	√
Molybdenum				√	√
Natural Graphite	√	√	√		
Natural Rubber	√				
Nickel				√	√
Niobium	√	√	√	√	√
PGMs**	√	√	√	√	√
Phosphorus	√			√	√
Phosphate rock	√				
Potash		√			
Rhenium		√	√	√	√
Rubidium		√			
Scandium	√	√	√		
Selenium					√
Silicon metal	√		√		√
Silver				√	
Strontium	√	√		√	√
Tantalum	√	√	√	√	√
Tellurium		√			√
Thallium					√
Titanium	√	√	√	√	√
Tin		√		√	√
Tungsten	√	√	√	√	√
Uranium		√			
Vanadium	√	√	√	√	√
Zinc				√	
Zirconium		√	√	√	√

*REEs: Light and heavy Rare Earth Elements; **PGMs: Platinum Group Metals

Figure 2: Lists of critical raw materials
for the European Union (2020), the United States of America (2018), Australia (2022), Japan (2018) and the Republic of Korea (2020). Own depiction based on Lee and Cha (2020) and the Australian Government (2022)

As shown in Figure 2, some raw materials are rated as critical by all countries/regions. These raw materials are typically the ones that are mainly produced by socio-economically and geopolitically unstable economies and that are, at the same time, crucial for the production of key technologies. An example is cobalt (Co). On the one hand, over 50% of this metal is mined in the Democratic Republic of the Congo and refined in China (Alves Dias et al. 2018), countries that are viewed as geopolitical unstable (World Bank 2019) and where conflicts have frequently led to supply disruptions in the past (Hatayama and Tahara 2018). On the other hand, cobalt is of high strategic importance for the energy and mobility transition because it is a crucial element in for example traction batteries and permanent magnets of wind turbines (BJMT/Ideal 2014; Nature Editorial 2021).

Some of the lists are frequently updated such as the lists of the EU, for which the evaluation of critical raw materials is revised every three to four years (European Commission 2010, 2014, 2017c, 2020b, 2023). Looking at the updates made on the latest list published in 2023 compared to the previous list from 2020, arsenic, feldspar, helium and manganese have been added as well as indium and natural rubber have been removed. Furthermore, the latest list of the EU newly includes copper and nickel as strategic raw materials, which describe raw materials used in technologies crucial for the green and digital transition as well as defense and aerospace projects (European Commission 2023). These updates in the lists of critical raw materials suggest that criticality may change over time, a fact that has also been highlighted by Ioannidou et al. (2019).

Other raw materials are rated as critical only by a few countries and/or regions. Examples of these raw materials are borate, natural rubber and phosphate rock, which are all identified as critical by the EU (European Commission 2020b), but are not seen as critical by the Australian Authorities (Australian Government 2022). This illustrates that the ratings of critical raw materials are, amongst others, specific to their geographical context. In this regard, Ioannidou et al. (2019) explained that site-specific circumstances regarding for example the existence of domestic production, national trade policies or preferences in the choice of technologies play an important role in the evaluation of criticality.

For a country such as Switzerland, evaluating the criticality of intermediate/final products and thus supporting the creation of resilient supply chains is of particular importance because its service-oriented economy depends almost exclusively on primary resources from abroad. As shown in Figure 1, technologies that are used in the "mobility", "energy" provision and storage as well as "ICT" (i.e. information and communication technology) sectors particularly rely on the supply of various raw materials. These three sectors fulfill key functionalities within the Swiss economy and increasingly comprise clean, innovative and digital technologies, which are of high strategic importance in view of Swiss sustainable development. The implementation and upscaling of such technologies are perceived as relevant innovations to decrease the country's total GHG emissions, i.e. greenhouse gases directly emitted in the country and emitted along its supply chains. Related technological innovations are for example seen in expanding renewable energy capacity (IPCC 2014), in increasing the share of electric vehicles (Hirschberg et al. 2016; Lattanzio 2020) and in accelerating digitalization, which, as explained by Mondejar et al. (2021), could enable a reduction of GHG emissions in the industry and agriculture areas. The need of such innovations becomes clear when looking at the current GHG emissions statistics and targets of Switzerland. The country plans to reduce by 50% its total GHG emissions by 2030 (compared to its releases in 1990) and to reach net zero by 2050 (Swiss Federal Council 2021a). However, so far, Switzerland has only achieved a marginal decrease in its domestic GHG emissions (see the decrease in emissions from 52.36 CO_2-equivalents in 2010 to 44.26 CO_2-equivalents in 2019 shown in Figure 3a). As illustrated in Figure 3b, the areas of the Swiss economy that contribute the most to the country's total GHG emissions are mobility (32% of total emissions), energy provision, i.e. heating for industry (18% of total emissions) and for households (16% of total emissions), and agriculture (14% of total emissions). While the emissions in agriculture stem mainly from animal husbandry and use of farmyard manure (Federal Office for the Environment 2023), the emissions in the other sectors originate from the production and use of related technologies. Thus, considering the strategic relevance of technologies used in the Swiss mobility, energy and ICT sectors and their complex supply chains, the focus of this thesis is on analyzing supply chains of products used within these three sectors.

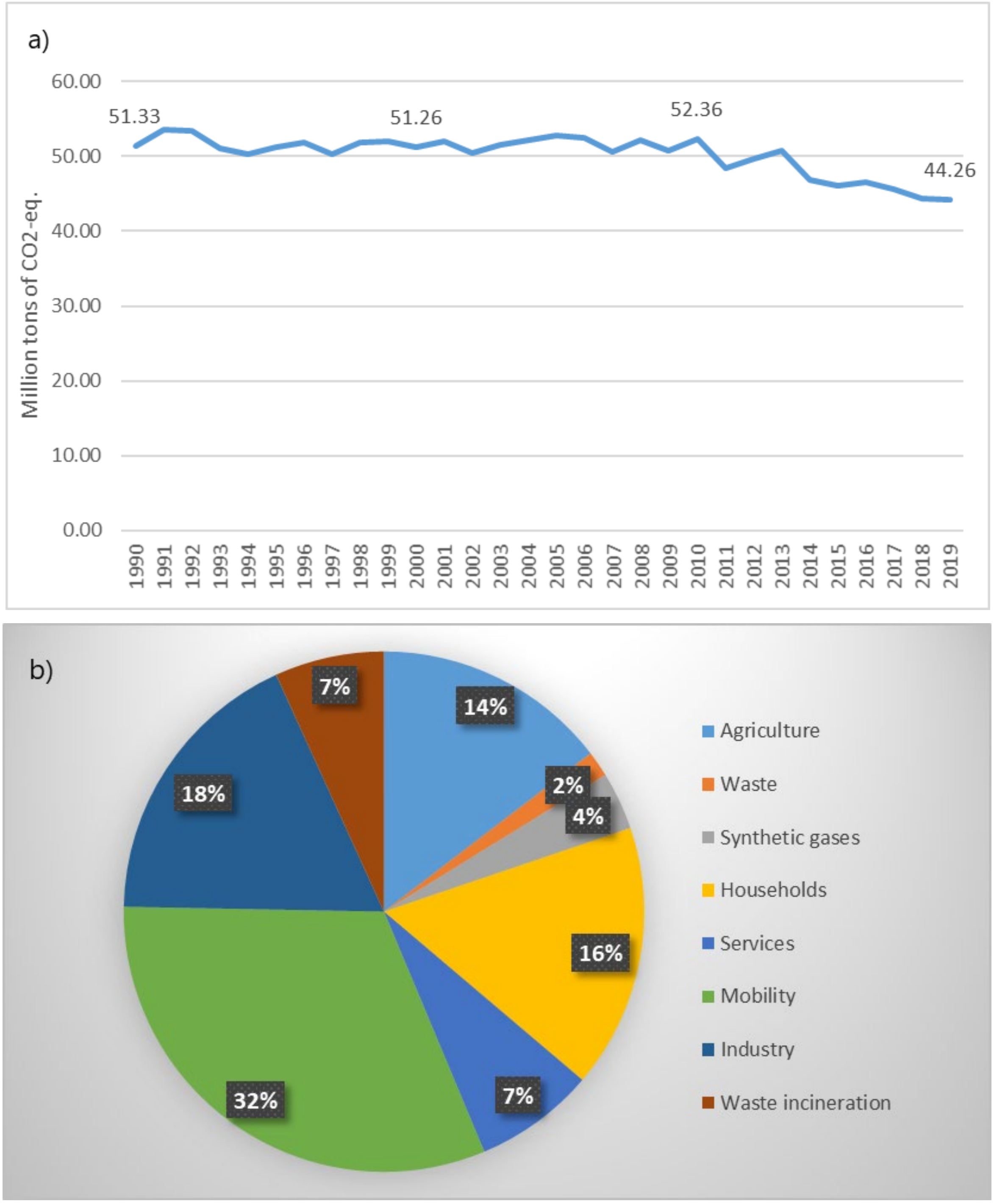

Figure 3: Description of greenhouse gas emissions in Switzerland
including the development of these emissions from 1990 until 2019 (a) and the greenhouse gas contributions from eight different areas of the Swiss economy in 2020 (b). Own depiction based on data from Ritchie et al. (2020) and BAFU (2022).

1.2 Problem formulation

In 2010, Kohl has already emphasized the dependency of the Swiss economy on resources from abroad and thus the need to integrate a resource strategy into Switzerland's foreign affairs activities in order to guarantee the security of its supply chains (Kohl 2010). Establishing such a resource strategy has gained even more relevance over the last few years. On the one hand, global supply chains linked to Swiss consumption have been affected by supply disruptions caused by for example the COVID-19 pandemic, the Brexit or the trade war between USA and China, respectively (Atteslander and Ramo 2022; Deloitte 2022; Revill 2019). Together, these three events have significantly contributed to the decline of 2.5% of the Swiss GDP (i.e. around 18.3 billion CHF) between 2019 and 2020 that has been reported by the International Monetary Fund (2021). Avoiding the impacts of such supply disruptions is getting particularly important in relation to supply chains for clean technologies e.g. in the area of mobility or energy provision, as their successful implementation and upscaling are essential to comply with the country's sustainable development strategy (see section 1.1). In terms of such supply risk mitigation, the Critical Raw Materials Act of the European Commission (2022b) has formulated four basic principles concerning the focus on strategic applications, the anticipation of risks, the creation of more resilient supply chains and the preservation of a strong and sustainable level playing field. Following these principles, an effective resource strategy for Switzerland needs to be concerned with, amongst others, analyzing supply bottlenecks along the important supply chains of Swiss consumption and identifying strategically relevant technologies associated with comparably low supply risks.

In order to identify such supply bottlenecks and technologies, approaches assessing supply disruption impacts have been developed within the field of criticality assessment (a list of these various approaches can be found in Schrijvers et al. (2020b)). However, three general problems exist with regard to the assessments performed with these approaches.

First, as highlighted by Schneider et al. (2013), Dewulf et al. (2015b) and Cimprich et al. (2019), assessments need to be established that allow for identifying supply disruption impacts along the full supply chain. Such assessments are particularly important in the case of complex global supply chains because, as emphasized by Ku et al. (2018), supply disruptions may affect processes anywhere along such supply chains. The need for such assessments has also become evident during the COVID-19 pandemic, which caused negative impacts on the production processes of raw materials, intermediate products and final products (Balleer et al. 2020; Kumar et al. 2020). However, the existing approaches have so far mostly assessed supply disruption impacts of the raw materials only (Schrijvers et al. 2020b). This thus poses the risk that decision-makers in public administrations and companies neglect important risk mitigation measures and miss crucial information to design resilient supply chains.

Second, criticality assessment approaches should not be limited in their scope of causes for supply disruptions, relevant time horizons and types of potentially affected material flows. Variations in possible causes are indicated by the various types of past events that led to supply disruptions. Examples are the increased inflation rate due to the Covid-19 pandemic (Balleer et al. 2020), trade restrictions due to the China-United States trade war (Bekkers and Schroeter 2020) as well as natural disasters, strikes and policy disputes, which describe events identified in the empirical study of Hatayama and Tahara (2018). Furthermore, variations in the relevant time horizons are highlighted by Ku et al. (2018) and Glöser et al. (2015) through an investigation of time scales related to supply disruption events. Events causing changes in the current market situation for example are relevant in the short-term (i.e. < 5 years), while events affecting expected future developments need to be analyzed in the medium-term (i.e. next 5 to 15 years) or long-term (i.e. a few decades). These specific time horizons have been distinguished by Erdmann and Graedel (2011) and Graedel et al. (2012). Finally, variations exist in the type of potentially affected material flows. This is for example indicated in the lists of critical raw materials presented in Figure 2, as these lists show that flows of abiotic materials such as cobalt and biotic materials such as natural graphite can equally be disrupted. Because several criticality assessment approaches do not consider these three different types of variations due to their limited scopes (Schrijvers et al. 2020b), there is a risk of overlooking certain supply disruptions during the decision-making process.

Third, the factors that provoke a risk of supply disruption need to be understood within criticality assessments. Frenzel et al. (2017) and Glöser et al. (2015) stress that the analysis of supply disruption risks should comply with the prescriptions from classic risk and decision theory defined by Cox (2009), where risk is expressed as the product of a probability and the consequence of an event. However, the set of indicators included in existing criticality assessment approaches does not necessarily represent the anticipated risks (Schrijvers et al. 2020b). According to Frenzel et al. (2017), a reason is that indicators are generally selected based on subjective expert opinion instead of based on empirical data verifying the indicator choices. Such false interpretations of risks can result in wrong decisions regarding risk management and, according to Frenzel et al. (2017), even deliver "worse than useless" results because there is often no linear relationship between probability and consequence. As suggested by Schrijvers et al. (2020b), a possible solution could be to follow the example of environmental Life Cycle Impact Assessment and establish clear cause-effect chains between the events that cause supply disruptions and the effects that the supply disruptions have on the considered supply chain processes. Following the examples given by Cimprich et al. (2019), indicators could be selected that allow for measuring these theoretical constructs.

1.3 Objectives

As service-oriented economies such as the Swiss economy are in need of identifying relevant supply risks along their global supply chains and implementing sustainable development strategies (see sections 1.1 and 1.2), there has overall been a strong interest in assessing supply disruption impacts within a sustainability assessment framework (Hackenhaar et al. 2022; Sonnemann et al. 2015). As suggested by

Sonnemann et al. (2015), an adequate option for such an assessment is to evaluate potential supply disruption impacts complementary to Life Cycle Assessment (LCA) as part of a broader Life Cycle Sustainability Assessment (LCSA) framework. Cimprich et al. (2019) have highlighted three motivations for such an integrated assessment. First, the assessment of environmental impacts in LCA is linked to a *functional unit* describing the function of the considered product system. Also connecting criticality assessment to this unit could provide additional information valuable for product-level design and management decisions. Second, LCA provides a practical tool to analyze "hotspots" in a product system by highlighting specific processes for which the contributions to potential environmental impacts are particularly large and it thus represents areas where the product's environmental "profile" needs improvements. Similarly, the processes associated with the highest impacts of supply disruptions could be identified and thus areas where risk mitigation is potentially required could be highlighted. Third, a bill of materials is typically constructed as part of LCA studies. The already identified physical flows could be considered for the criticality assessment, which would allow for reducing the efforts regarding data collection. Besides these different motivations, assessing supply disruption impacts within LCSA has also benefits regarding the interpretation of the assessment results. Following Sonnemann et al. (2015), Bach et al. (2016) and Cimprich et al. (2017), such an assessment complements frameworks that are already used for product-level design and management decisions and thus allows for avoiding burden-shifting between different processes of a supply chain as well as between supply disruption impacts and environmental, economic and social impacts.

Considering the high risks of supply disruptions within global Swiss supply chains over the next few years and the so far widely missing possibilities to analyze these risks along full supply chains (see section 1.2), this dissertation is dedicated to the development of a new method for criticality assessment and the provision of information about supply disruption impacts along global supply chains. This is done, in particular, for the Swiss mobility, energy and ICT sectors, because, as explained in section 1.1, especially technologies used within these three sectors are vulnerable to supply disruptions and are particularly relevant for the green and digital transition in Switzerland. Considering the need for such a transition, the "Open Assessment of the Swiss Economy and Society" (OASES) project (https://nfp73.ch/en/projects/open-assessment-of-swiss-economy-and-society) funded by the Swiss National Science Foundation, which the presented research work contributed to, also focused on sustainability assessment particularly related to supply chains within these three sectors. Thus, the overall objective of this dissertation is to answer the following question:

"What are potential supply disruption impacts along the global supply chains within the Swiss mobility, energy and ICT sectors?"

Answering this question requires the identification of an approach that allows for evaluating potential supply disruption impacts along the full supply chain. Considering the different motivations and benefits of an integration of criticality assessment into LCSA (see explanations of the motivations and benefits above), the goal is to identify an approach that allows for such an assessment within LCSA. The applicability of such an approach should then be shown for the example of supply chains for technologies used within the mobility, energy and ICT sectors in Switzerland. Therefore, the work of the present thesis follows the following three research questions:

- RQ1: How can potential supply disruption impacts be evaluated along full supply chains in the short- and medium-term within the Life Cycle Sustainability Assessment framework?
- RQ2: What are short-term impacts of potential supply disruptions along the supply chain of electric vehicles used in Switzerland?
- RQ3: What are short-term impacts of potential supply disruptions along the supply chains within the Swiss mobility, energy and ICT sectors?

1.4 Thesis structure

Figure 4 shows the structure of the thesis with a description of the chapters corresponding to the three, above listed research questions. Following the introduction section in Chapter 1, the state of research is explained in Chapter 2, which introduces three methods that are useful to answer the research questions. Chapter 3 then addresses **RQ1** by describing the development of the "SPOTTER (A**s**sessing potential su**p**ply disrupti**o**n impacts along **t**he supply chain in the shor**t-** and m**e**dium-term within the LCSA f**r**amework) approach" as well as by identifying and describing indicators that are suitable to be used for a definition of potential supply disruption impacts with SPOTTER. Chapter 4 investigates **RQ2** by applying the SPOTTER approach to a first case study, where short-term impacts of potential supply disruptions are identified along the aluminium and cobalt supply chains of electric vehicles used in Switzerland. Chapter 5 introduces an advancement of the SPOTTER approach allowing for an assessment suitable on the sectoral level (i.e. answering **RQ3**) and applies this advanced SPOTTER approach to a second case study, where potential supply disruption impacts are identified for the Swiss mobility, energy and ICT sectors in the short-term. Chapter 6 provides a critical discussion of the findings of the thesis. Last but not least, conclusions are drawn and an outlook on possible future research direction is provided in Chapter 7.

Several research articles have been published or are currently under review as part of regular scholarly research activities underlying this thesis. Parts of sections 2.3 and 2.5 as well as Chapter 3 conform with Berr et al. (2022). The content of Chapter 4 is based upon Berr et al. (2023). The content of Chapter 5 is based upon the manuscript *Assessment of Short-Term Supply Disruption Impacts for the Swiss*

Mobility, Energy and ICT Sectors – Application of the SPOTTER Approach (Berr et al. forthcoming), which is currently under review at the Journal of Cleaner Production.

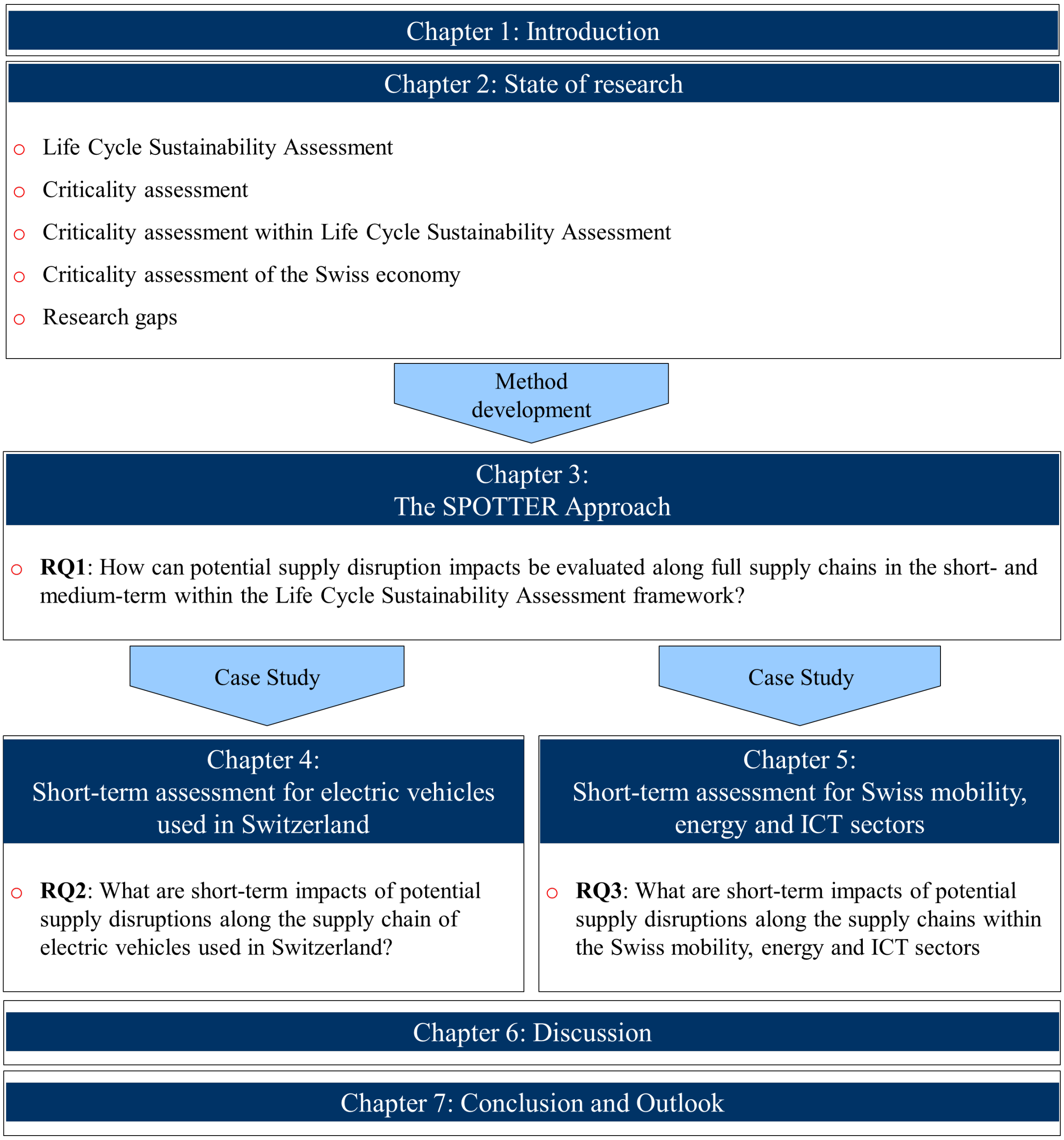

Figure 4: Structure of the dissertation

"Many of our best opportunities were created out of necessity"
~ Sam Waton

2. State of research

The state of research first provides an overview of existing methods and research outcomes used to address research questions similar to those listed in this thesis and then explains the research gaps investigated in frame of this thesis. Section 2.1 and 2.2 introduce the tool of LCSA and the method of criticality assessment, respectively. Section 2.3 gives an overview concerning the integration of criticality assessment into this LCSA framework. Existing studies for criticality assessment of the Swiss economy are described in section 2.4 and the identified research gaps are explained in section 2.5.

2.1 Life Cycle Sustainability Assessment

Various instruments in form of indicators/indices, product-related assessments or integrated assessments are available to perform sustainability assessments. The most established and well-developed tool in the category of product-related assessments is LCA (Ness et al. 2007). It allows for assessing environmental impacts along the full product life cycle comprising resource extraction, raw material production and intermediate/final product manufacturing processes as well as the use and end-of-life (EoL) treatment phase. Assessing impacts from a life cycle perspective is particularly relevant in view of sustainable development as it has the advantage of recognizing and avoiding trade-offs among the involved processes (Frischknecht 2020).

2.1.1 Historical development and general characteristics

The Brundtland report has provided a commonly accepted definition of sustainable development "Sustainable development is development that meets the needs of the present without comprising the ability of future generations to meet their own needs" (United Nations 1987). Based on the Brundtland report, the Agenda 21 (United Nations 1992) has been formulated, which contributed to the global discussion on sustainable development by highlighting the issues related to the development gap between the Global North and Global South and the need for linking social and economic development with environmental protection. The common understanding of sustainability as an interconnection of impacts subdivided according to three pillars of environment, economy and society has then evolved (Purvis et al. 2019). This interpretation later resulted in the formulation of the triple bottom line by Elkington (1999), an accounting framework considering economic prosperity, environmental quality and social justice. More recently, within the 2030 Agenda for Sustainable Development (UN General Assembly 2015), a plan of action for people, planet and prosperity has been established and the need to strengthen universal peace and collaborative partnership of all countries and stakeholders has been emphasized. This plan of action has been presented in the form of the 17 Sustainable development Goals describing an urgent call of action by developed and developing countries (United Nations 2015).

These historical developments regarding the interpretation and implementation of sustainable development have inspired the development of the so-called Life Cycle Sustainability Assessment framework, a framework allowing for an assessment of product life cycles in accordance with the three commonly recognized sustainability pillars, i.e. environment, economy and society (Valdivia et al. 2021). (Environmental) LCA, Life Cycle Costing (LCC – an analysis of all costs associated with the product life cycle), and Social Life Cycle Assessment (SLCA – an assessment of social impacts along the product life cycle, are combined in the LCSA framework. Kloepffer (2008) thus proposes the following conceptual scheme for LCSA (Equation (1)):

$$LCSA = LCA + LCC + SLCA \tag{1}$$

According to this scheme, LCSA is performed as separate assessments for the three methodologies, i.e. LCA, LCC and SLCA. Further types of LCSA, where impact assessments of these up to three methdologies are combined, have also been suggested. A list of sample approaches for the different types of LCSA is provided in the systematic review of LCSA performed by Costa et al. (2019). However, types of LCSA other than the option of separate assessments are rarely considered, as they are more difficult to perform due to the different degrees of methodological development maturity among the three methodologies (Costa et al. 2019; Valdivia et al. 2021).

2.1.2 Assessment structure

Guidelines for the performance of LCSA as separate assessments of LCA, LCC and SLCA have been proposed by the UNEP/SETAC Life Cycle Initiative (2011). These guidelines follow the four iterative phases *Goal and Scope Definition*, *Life Cycle Inventory Analysis* (LCI), *Life Cycle Impact Assessment* (LCIA) and *Interpretation*. The four phases are also established in the ISO standards for the performance of LCA (ISO 2006a, b). Figure 5 outlines a possible procedure of an LCSA based on these four phases with brief examples. The Goal & Scope definition is thereby performed once for all three methodologies, while, as indicated with the colors green, red and blue, the LCI and LCIA are carried out separately for LCA, SLCA and LCC. The interpretation phase, where it is explained how the different results from LCA, SLCA and LCC are analyzed, is again conducted for all three methodologies together.

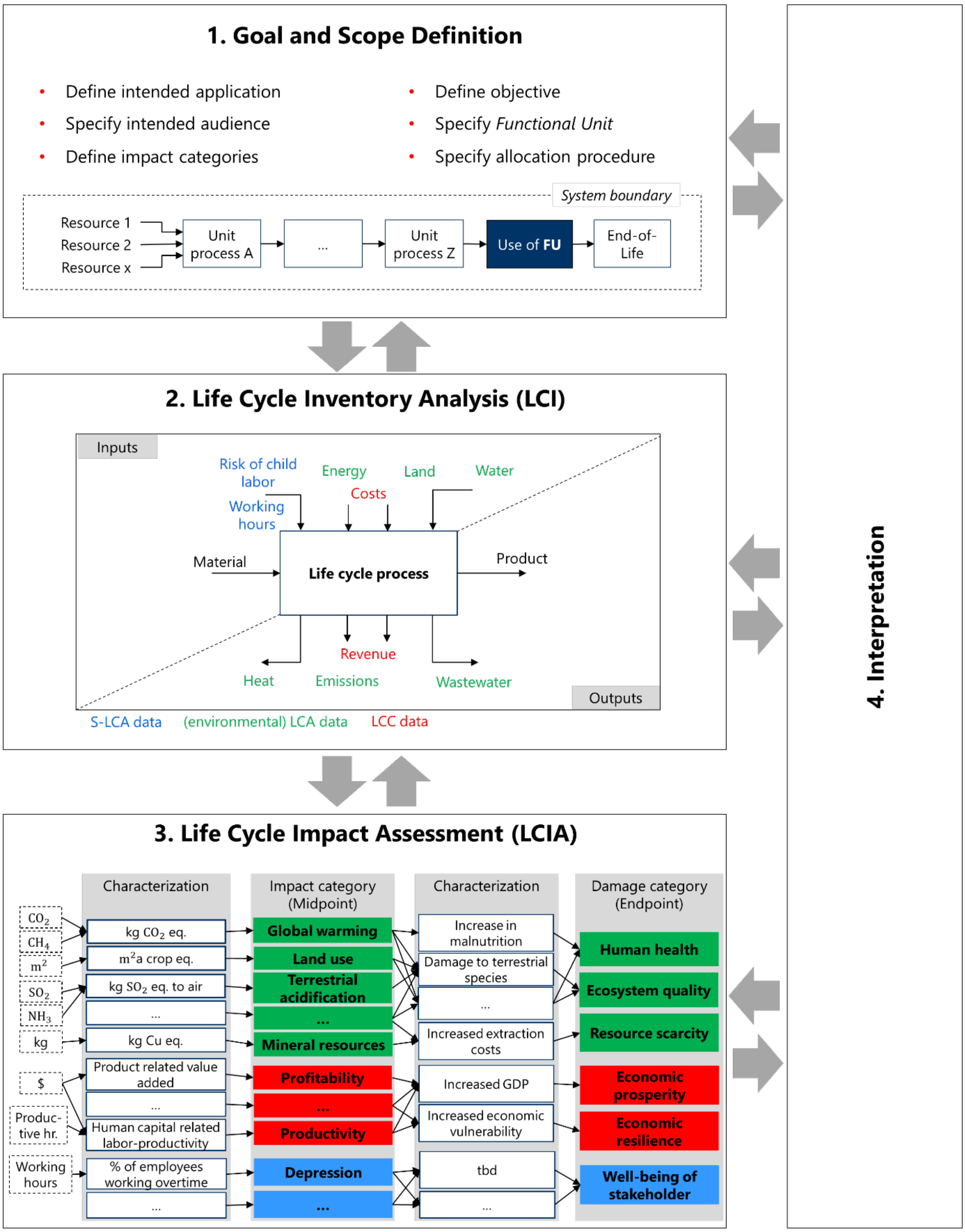

Figure 5: Framework for a Life Cycle Sustainability Assessment
including the four phases of Life Cycle Assessment described in ISO 14040 (ISO 2006a). The *Goal and Scope Definition* and *Life Cycle Inventory Analysis* are described using information from the UNEP/SETAC Life Cycle Initiative (2011). The *Life Cycle Impact Assessment* is illustrated by possible midpoint and endpoint impact categories with examples for the impact characterization. The environmental impact assessment (depicted in green) is based on the LCIA method ReCiPe 2016 (Huijbregts et al. 2016). The economic impact assessment (depicted in red) and social impact assessment (depicted in blue) is based on the impact pathways proposed in the study of Neugebauer et al. (2016) and the Social Hotspot Database (Benoit Norris and Norris 2015; Benoit Norris et al. 2019), respectively. Own depiction based on Wietschel (2022).

Goal & Scope Definition. Following the procedure described in Figure 5, an LCSA starts with the definition of the goal. Here, similar to LCA, the reason for the study, the target audience and the intended application are specified. A crucial element of the scope in both LCA and LCSA is the definition of the *Functional Unit* (FU). It describes the quantified performance that the analyzed product system delivers to the end-user and provides a basic value to which inputs and outputs of the product system are scaled in the LCI. The FU is thus usually defined as a service, a mass or an economic value (Hauschild et al. 2017). With regard to an LCSA, the FU needs to describe not only the technical but also the societal utility of a product to be at the same time applicable for LCA, LCC and SLCA. Furthermore, the scope includes a definition of the system boundaries. Following the guidelines of the UNEP/SETAC Life Cycle Initiative (2011), these boundaries are to be defined consistently for all three assessments and cover unit processes relevant to at least one of the three methodologies. Finally, the relevant impact categories for LCA, SLCA and LCC are selected as well as, similar to LCA, the allocation procedure in case of multiple output processes is described (UNEP/SETAC Life Cycle Initiative 2011).

Life Cycle Inventory Analysis. In the LCI phase, all inputs and outputs are collected that are required to provide the function described by the FU. These inputs and outputs comprise different types of elementary flows depending on the type of methodology, i.e. LCA, SLCA or LCC. Biophysical flows (i.e. mass, energy and emission flows) are collected for the LCA (green color in Figure 5), monetary flows are collected for the LCC (red color in Figure 5) and labor-related flows are collected for the SLCA (blue color in Figure 5) calculations, respectively (Mancini et al. 2016). Due to the different characteristics of these flows, the required data for an LCSA usually needs to be acquired from different data sources. An often-used source in order to quantify the biophysical flows is the database ecoinvent, one of the most detailed, transparent unit process life cycle inventory databases in the world (Wernet et al. 2016). Another source, used in studies such as the ones of Beylot et al. (2020) or Sen et al. (2019), is EXIOBASE, a database providing environmentally extended multi-regional input-output (MRIO) tables (Merciai and Schmidt 2018). While ecoinvent shows a high granularity along the covered life cycles, EXIOBASE shows a complete picture of all the exchanges within the economy based on aggregated categories of materials and processes (Beylot et al. 2020). To collect monetary flows, a possible source is BACI, a database providing material/product-related trade data in monetary and mass units (Gaulier and Zignago 2010). Labor-related flows are based on quantitative data in the case of for example working hours as well as semi-quantitative or qualitative data in the case of risk of child labor (UNEP/SETAC Life Cycle Initiative 2011). Databases such as the Social Hotspot Databases (SHDB) (Benoit Norris and Norris 2015) help to gather this type of data but still, context-specific information regarding the geography and the socio-economic conditions related to the analyzed system is often missing (Zamagni et al. 2016).

Life Cycle Impact Assessment. The LCI phase is followed by the LCIA phase. Here, as recommended by the UNEP/SETAC Life Cycle Initiative (2011), the classification and characterization steps described in the ISO standards 14040 and 14044 (ISO 2006a, b) are performed as the minimum required and mandatory steps. Within the classification steps performed in LCA, LCC and SLCA, the collected elementary flows are assigned to selected impact categories, also called midpoints. Figure 5 illustrates this assignment exemplarily for different flows and impact categories considered in LCA, LCC and SLCA. An example in the case of LCA is the allocation of the amounts of CO_2 and CH_4 emissions and other GHG emissions to the impact category *global warming*. Within the characterization step, impact scores are calculated and aggregated into impact category results. Here, so-called characterization factors (CFs) that describe the cause-effect relationship between the elementary flow and the specific impact are used as weighting factors. After an aggregation into impact categories, the impacts can again be characterized into damage categories, also called endpoints. According to Bare et al. (2000), endpoint category results often have a higher relevance but a lower certainty in comparison to midpoint category results. Following the UNEP/SETAC Life Cycle Initiative (2011) and as also stated in the ISO 14044 standards (ISO 2006b), the calculation of endpoint category results is an optional step.

Figure 5 describes the definition of CFs exemplarily for impact and damage categories considered in LCA (green color), LCC (red color) and SLCA (blue color). Following, sample impact and damage categories are described and the definition of related CFs and impact scores are explained for the three methodologies.

In the case of LCA, various already established LCIA methods, which differ in their way of quantifying environmental impacts, are available. In Figure 5, the categories included in the LCIA method ReCiPe 2016 (Huijbregts et al. 2016) are considered as this method has been suggested as an interim solution for environmental impact assessment by the European Commission (2011). For the example of the impact category *global warming*, the results are calculated according to Equation (2):

$$GW_{x,mid} = m_x * GWP_{x,mid}$$
$$GWP_{x,mid} = \frac{dC_x}{dE_x} * \frac{dRF}{dC_x} * \frac{dTEMP}{dRF} \tag{2}$$

The global warming related to the emission of a specific greenhouse gas *x* ($GW_{x,mid}$) is calculated based on the first formula of Equation (2), where m_x is the amount of this greenhouse gas *x* and $GWP_{x,mid}$ is the respective midpoint CF describing the potential of global warming per greenhouse gas. Following De Schryver et al. (2009), $GWP_{x,mid}$ is calculated based on the second formula of Equation (2), where dC_x is the change in air concentration of greenhouse gas *x* (ppb), dE_x is the change in emission of greenhouse gas *x* ($kg * year^{-1}$), *dRF* is the change in radiative forcing ($W * m^{-2}$) and *dTEMP* is the change in global mean temperature (°C). The $GWP_{x,mid}$ is used to aggregate the substances in relation to values for *kg emitted CO_2 equivalent*. 1 kg of emitted methane for example corresponds to about 30 kg of emitted CO_2, as it has around 30 times stronger global warming potential than CO_2.

As global warming, land use and terrestrial acidification lead to damage to terrestrial species due to increased temperatures, land transformations or decreases in soil pH, these types of impacts can be aggregated into the damage category *Ecosystem quality* (Huijbregts et al. 2016). Following De Schryver et al. (2009), the related endpoint CF ($CF_{x,end}$) in case of global warming can be calculated according to Equation (3), where $dIMPACT_{end}$ describes the marginal change in damage for the environmental endpoint *end*.

$$CF_{x,end} = \frac{dC_x}{dE_x} * \frac{dRF}{dC_x} * \frac{dTEMP}{dRF} * \frac{dIMPACT_{end}}{dTEMP} \tag{3}$$

In contrast to LCA, the performance of LCC, as it is recommended by the UNEP/SETAC Life Cycle Initiative (2011), does not involve a step comparable to LCIA. Here, the impacts are measured based on an aggregation of costs. However, a potential evaluation of the economic dimension included in the LCSA framework is described by Neugebauer et al. (2016), who suggest a characterization model for two economic areas of protection, i.e. *economic stability* and *wealth generation*. Figure 5 represents the two damage categories, i.e. *economic prosperity* and *economic resilience*, and two of the five impact categories, i.e. *profitability* and *productivity*, that are considered in this characterization model. For example, profitability is characterized by the microeconomic value added. Productivity in turn is understood as a benefit related to employee engagement and human development. The increase in profitability and productivity as well as other economic benefits lead to an increased GDP and can thus be aggregated in the damage category *economic prosperity*.

In the case of SLCA, the guidelines of UNEP/SETAC Life Cycle Initiative (2009) adapt for the performance of SLCA the six impact categories (i.e. *human rights*, *working conditions*, *health & safety*, *cultural heritage*, *governance* and *socio-economic repercussions*) and related subcategories, and five stakeholder groups (i.e. *workers*, *local community*, *society*, *consumers* and *value chain actors*) that have been defined by Benoit et al. (2007). However, similar to LCC, harmonized LCIA methods are so far missing for SLCA because there is a lack of uniformity in the indicators to be used for the definition of the CFs (Costa et al. 2019; Zamagni et al. 2016). Figure 5 thus describes an impact pathway that is suggested by Benoit Norris and Norris (2015) but not established in SLCA. According to Benoit Norris and Norris (2015), excessive working time leads to higher stress levels for workers, which may cause depression (a midpoint). Excessive working time could be characterized by the *percentage of employees working more than 48 hours per week* as proposed by Benoit Norris et al. (2019). Depression and other health issues will affect the well-being of stakeholders (an endpoint). Suitable indicators to describe this causal relationship are however still missing.

Interpretation. In the fourth and last phase, conclusions are drawn and recommendations are made. The aggregation and weighting of results from LCA, LCC and SLCA would lead to lower complexity in the representation of results and thus facilitate the decision-making. To perform such an aggregation, Traverso et al. (2012) suggest a Life Cycle Sustainability Dashboard, which represents scores combining the result of the three methodologies based on equal and individual weighting schemes. Müller and Hiete

(2021) suggest the definition of an aggregated sustainability score using weighting schemes suggested by experts. However, the UNEP/SETAC Life Cycle Initiative (2011) advocates for interpreting the results of the LCA, LCC and SLCA separately and does not recommend the aggregation of these results. The reasons for this recommendation are an immature development and implementation of LCSA and disparities in the individual aims of the three methodologies.

2.1.3 General methodological issues

Overall, LCSA is seen today as a useful tool for decision-making regarding sustainable development, as it provides a more holistic understanding of sustainability of products and processes compared to existing environmental and sustainability tools. However, it is still in an immature stage and has several shortcomings (Costa et al. 2019).

First of all, there is currently no consensus in LCSA on defining the impact categories that should be assessed, due to the unavailability or missing harmonization of established methods for LCIA (Costa et al. 2019). Furthermore, LCSA lacks a consideration of interdependencies among the environmental, social and economic dimensions (Gbededo et al. 2018). Finally, LCSA is criticized as being rather confusing for decision-making due to the combination of a relatively large number of indicators (Hauschild et al. 2017).

At the same time, it is highly debated how to assess the impacts related to the use of natural resources in LCA or LCSA studies (Dewulf et al. 2015b; Drielsma et al. 2016). An expert task force established by the Life Cycle Initiative hosted by the UN Environment reviewed related LCIA methods (Sonderegger et al. 2020). Their review shows four different categories of methods. The first category includes methods referring to the concept of the reduction in resource stocks measured by for example a ratio between annual extraction rates and the natural resource stocks squared (Klinglmair et al. 2013). The second category comprises methods describing the consequences of current resource use on the potential of resource extraction in the future. This aspect is for example analyzed with ReCiPe 2016 (Huijbregts et al. 2016) by considering marginal ore grade declines and surplus costs. The third category covers thermodynamic accounting methods that measure the extraction of exergy embedded in the resource (Dewulf et al. 2007). The fourth category includes supply risk methods such as the ESSENZ approach (Bach et al. 2016) and the GeoPolRisk approach (Gemechu et al. 2015b) that assess raw material criticality. As the development of methods included in the fourth category is of particular interest in this thesis, it will be discussed in a separate section (section 2.3). The expert task force has thus not agreed on a universally accepted interpretation of resource scarcity in LCIA methods but it provided guidance for the application of LCIA methods, which is described in the follow-up study of Berger et al. (2020).

2.2 Criticality assessment

2.2.1 Historical development and general characteristics

Due to increasing concerns about supply disruptions, a method that allows evaluating risks of supply disruption related to material use, i.e. the criticality assessment, has been of wide interest to governments, consultancies and academic institutions in the last few years (Graedel and Reck 2016). Companies and policymakers apply criticality assessment approaches e.g. for the selection of materials and products, for the design of supply chains, for the decision-making regarding investments, trade agreements and collaborations, for the prioritization of research projects and policy agendas as well as for the identification of supply risk mitigation measures (Buijs et al. 2012; Schrijvers et al. 2020b). A report published by the National Research Council (NRC 2008) has introduced the very first systematic way of measuring criticality, where the criticality of minerals used by the US economy is illustrated in a two-dimensional matrix describing the supply risk (referred to as "supply disruption probability" in this thesis[1]) on the x-axis and the impact of supply restriction on the y-axis. Other authors refer to the second dimension (i.e. impact of supply disruption) as economic importance, e.g. the European Commission (2010), or vulnerability to supply disruption, e.g. Graedel et al. (2012).

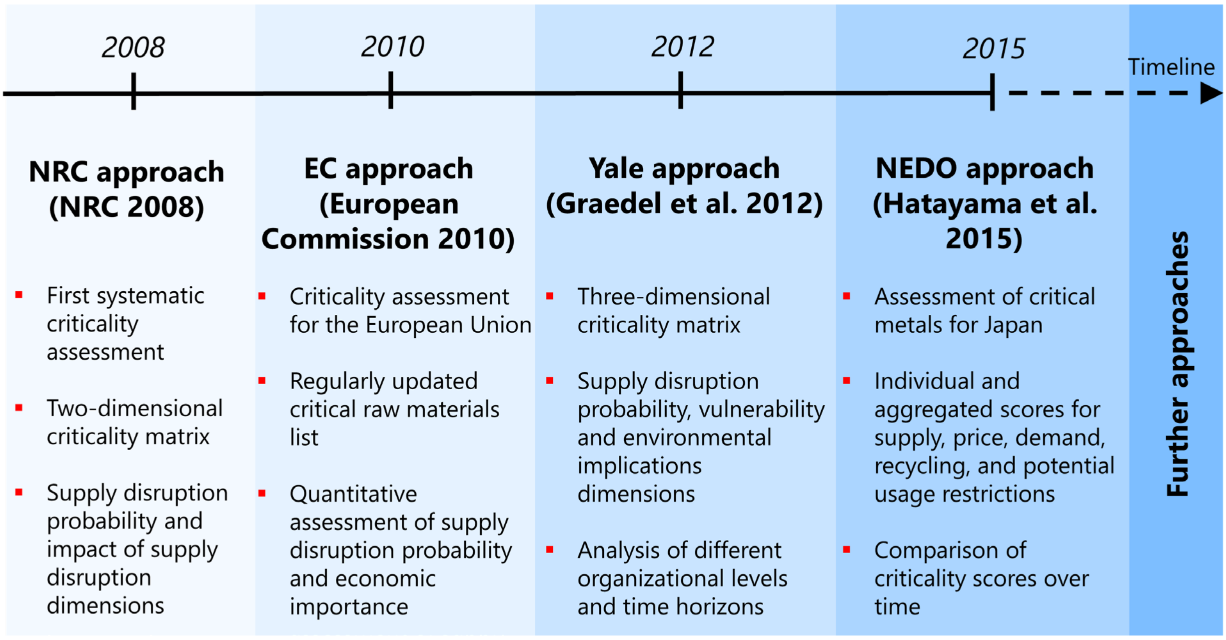

Figure 6: Pioneering criticality assessment approaches
and descriptions of their timeline and main contributions in the field of criticality assessment. These approaches comprise the National Research Council (NRC) approach (NRC 2008), the European Commission (EC) approach (European Commission 2010), the Yale University (Yale) approach (Graedel et al. 2012) and the New Energy and Industrial Technology Development Organization (NEDO) approach (Hatayama and Tahara 2015).

[1] Frenzel et al. (2017) and Glöser et al. (2015) explain, by referring to the classical risk theory (Cox 2009), that some of the criticality assessment approaches including the one of the NRC (2008) use the term "supply risk" to describe not an actual risk but a probability of supply disruption.

After the development of the NRC approach, several approaches have been developed in the field of criticality assessment. A list of approaches is for example provided by Schrijvers et al. (2020b). The four approaches shown in Figure 6 (i.e. NRC, EC, Yale and NEDO approaches) are often perceived as pioneering work in the field. These approaches have frequently been applied or adapted and have been included in several review studies, such as those performed by Erdmann and Graedel (2011), Achzet and Helbig (2013), Graedel and Reck (2016) and Schrijvers et al. (2020b).

The European Commission (2010) has developed a quantitative approach for a criticality assessment of raw materials used in European countries. With this approach, raw materials are assessed regarding their supply disruption probability and economic importance for the European economy in a two-dimensional matrix and critical raw materials are identified based on horizontal and vertical thresholds. This assessment is regularly updated (see the studies of the European Commission (2014), the European Commission (2017c), the European Commission (2020b) and the European Commission (2023)) and used to establish the list of critical raw materials for the EU. As shown in Figure 2, the list published in 2020 contains 30 raw materials. Note that the updated list for the EU from 2023 comprises 34 raw materials rated as *critical* or *strategic* raw materials. Several countries including the United States, Australia, Japan and the Republic of Korea have followed the example of the EU and established their own lists of critical raw materials. For example, the United States Geological Survey (USGS) has identified 35 critical raw materials for the United States (Fortier et al. 2018).

With the Yale approach (Graedel et al. 2012), a criticality assessment based on the three different dimensions *supply disruption probability*, *vulnerability to supply disruption* and *environmental implications* has been proposed. Criticality scores are illustrated in a three-dimensional matrix, in which the different levels of criticality are defined by the Euclidean distance to the origin of the criticality plot. Other features of this approach are that criticality can be assessed over two different time horizons (i.e. in the next 5 to 10 years and over a few decades) and on different organizational levels (i.e. national, corporate and global levels). According to Graedel et al. (2012), these separate assessments are important because evaluations over a single time frame or organizational level cannot adequately address the complete spectrum of criticality.

The NEDO approach (Hatayama and Tahara 2015) introduces an assessment specifically used for identifying critical metals used in an Asian country like Japan. Their analysis of supply, demand, price, recycling and potential usage restrictions suggests the consideration of new aspects in the field of criticality assessment, next to the supply restrictions, which are already assessed in the three previous approaches. Furthermore, a comparison of their latest results with earlier criticality scores suggests the consideration of potential changes in criticality levels over time.

The variety of existing criticality assessment approaches indicates the unavailability of a commonly accepted way of measuring criticality, which might be due to a missing universal definition of criticality (Schrijvers et al. 2020b). Indeed, criticality is perceived as context-dependent (Sonnemann et al. 2015) and a "matter of degree" (Bradshaw et al. 2013) that is sensitive to the time and location under investigation (Ioannidou et al. 2019). Schellens and Gisladottir (2018) have reviewed the current discourse in criticality assessment and provided based on their review a general definition of criticality that respects the classical risk theory (Cox 2009). According to their definition, critical materials are of "decisive importance ranked according to a hierarchy of human need" and "attended with uncertainty or a threat".

The importance described in the definition by Schellens and Gisladottir (2018) is interpreted differently across the literature. For example, the EC approach (European Commission 2010) considers economic importance because of its focus on a large economy that is vulnerable to supply disruption due to high reliance on imports. The economic importance related to the use of raw materials is thereby defined by the value added of the economic sectors, in which the raw material is used (European Commission 2010). The approach designed for the U.S. economy (Humphries 2019) in turn is concerned with strategic importance, as it should align with the strategy regarding the security of critical raw material supply in the United States. Following this strategy, a material is critical when (i) it is crucial for economic and national security, (ii) it is vulnerable to supply disruption and (iii) a supply disruption would have severe consequences on the economy or national security due to its essential function in manufacturing processes (Trump 2017). Other approaches (Roelich et al. 2014; Simon et al. 2014) focus on technological importance and thus aim to emphasize the exceptional functionalities of the used materials.

The threat described in the definition by Schellens and Gisladottir (2018) is again interpreted differently across the approaches, which is shown by their choices of events potentially leading to supply disruptions. While there is no consensus on the types of events that need to be considered for a criticality assessment (Dewulf et al. 2016), Schrijvers et al. (2020b) show certain tendencies in the selection of events. According to their study, geopolitical instability and resource depletion are for example among the most frequently analyzed events.

2.2.2 Assessment structure

While the interpretation of criticality is different among the existing approaches, the approaches generally follow a similar structure (Schrijvers et al. 2020b). This generic structure of a criticality assessment is described in Figure 7. It consists of the *goal and scope definition*, the *indicator selection*, the *indicator evaluation and aggregation* as well as the *interpretation and communication of results*.

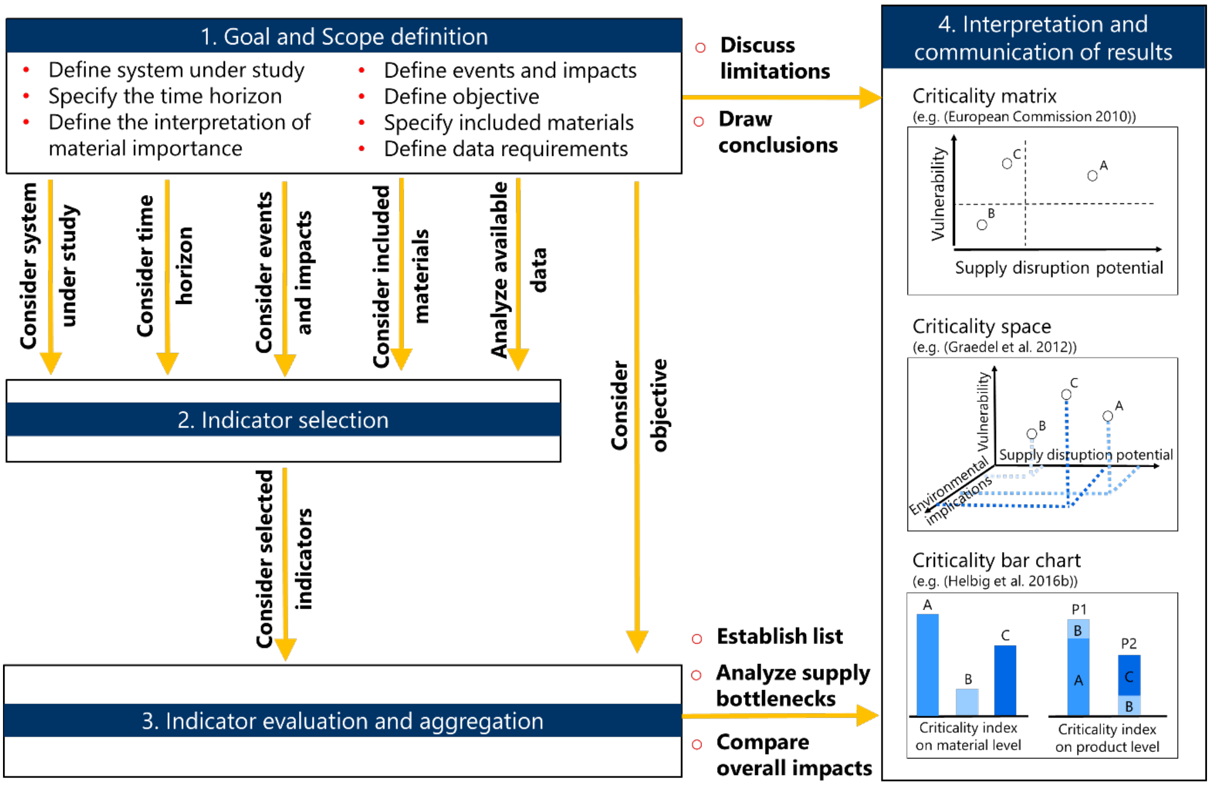

Figure 7: Generic structure of criticality assessment.
Visualization options are described based on imaginary values for the materials A, B and C as well as for the products P1 and P2. Own depiction based on Figure 2 in Schrijvers et al. (2020b) and Figure 1 in Achzet and Helbig (2013).

Goal and scope definition. In the first step, the system under study, the time horizon, the interpretation of the material importance, the type of supply disruption events and impacts, the objective, considered materials as well as data requirements are defined.

Systems under study are usually a national economy, a company or a product (Schrijvers et al. 2020b). As the criticality of a material may vary over time, the time horizon related to the study is determined. Graedel et al. (2012) suggests a distinction between short-term (i.e. next 5 years), medium-term (i.e. in 5 to 10 years) and long-term (i.e. a few decades). As described before, the material importance is interpreted from either an economic, a strategic or a technological perspective. The analyzed events are either country-specific, company-specific or global. Country-specific events such as *geopolitical instability* refer to conditions in specific countries, company-specific events such as *company supply concentrations* represent corporate market situations and global events such as *price volatility* refer to global supply and demand imbalances (Bach et al. 2017b). The assessed socio-economic impacts are either cost variability resulting from increased prices or limited availability resulting from a reduced or missing input (Frenzel et al. 2017). The objectives of criticality studies are generally (i) to raise awareness regarding supply and demand imbalances (ii) to identify needs for mitigating criticality and to suggest suitable mitigation measures or (iii) to provide a pre-screening that helps to prioritize information to be gathered in detailed studies. Most assessments do not include all types of materials but only a set of specific materials (Schrijvers et al. 2020b). This set is either defined by anticipating the most critical materials beforehand based on expert judgment, as done in the NEDO approach (Hatayama and Tahara 2015), or by performing a separate vulnerability analysis, like in the approach of Kolotzek et al. (2018). The data requirements comprise quantitative and qualitative data that is usually acquired from a variety of sources. Most commonly considered sources are geological surveys, the World Bank, scientific literature, industry reports and expert judgment (Schrijvers et al. 2020b).

Indicator selection. In the second step, suitable indicators are selected based on elements of the Goal and Scope definition. Here, the following four criteria are usually considered during the selection: first, indicators need to be suitable to represent the considered supply disruption events and impacts. Second, indicators need to align with the system under study, since, as shown by Graedel et al. (2012) and Bach et al. (2016, 2017b), different vulnerability indicators are suitable for assessments on a national, corporate or product level. Third, indicators need to refer to supply and demand changes over the considered time horizons because, as shown in the Yale approach (Graedel et al. 2012) and by Erdmann et al. (2011), the relevant time horizons vary between the evaluations with different indicators. Fourth, indicators need to allow for covering included materials or need to be quantifiable with the available data for the study are excluded or replaced.

Indicator evaluation and aggregation. In the third step, the selected indicators are first quantified for the individual materials and then, if required based on the objective, aggregated into scores for individual criticality dimensions or criticality indices. The different kinds of indicator aggregations are further explained in section 2.2.5. In line with the objective of the study, the derived criticality scores are then used to either establish lists of critical materials (European Commission 2020b; Fortier et al. 2018), analyze supply bottlenecks (Blagoeva et al. 2016; Moss et al. 2013), or compare the overall impacts of competing technologies (Helbig et al. 2016b; Henßler et al. 2016).

Interpretation and communication of results. Last but not least, in the fourth step, the criticality scores are visualized and the relative criticality of materials is interpreted based on these visualizations. Common visualization options are shown in Figure 7. These options are either a two-dimensional criticality matrix with defined vertical and horizontal thresholds, as used for example by the European Commission (2010), a criticality space considering Euclidean distances to the origin of the plot, as described for example by Graedel et al. (2012), or criticality bar charts as utilized for example by Helbig et al. (2016b). Finally, limitations are discussed and conclusions are drawn considering the original goal and scope definition.

2.2.3 General methodological issues

While the criticality assessment has been advanced over time through the development of several approaches, existing review articles state that some fundamental methodological issues remain. First, Erdmann and Graedel (2011) and Schrijvers et al. (2020b) highlight a lack of transparency, a low convergence of methodologies as well as widely missing sensitivity and uncertainty analysis in criticality assessment. Second, Frenzel et al. (2017) emphasize missing compliance of the current criticality assessment methodologies with the classic risk and decision theory even though criticality assessments aim to represent risks of supply disruption. Following their explanations, the correct way of analyzing such risks is by considering the probability of occurrence of a supply disruption event associated with the consequences of the event on the system and by indicating equal risk levels for example with hyperbolas in a two-dimensional matrix including these two risk dimensions. Other than that, Frenzel and colleagues have not found any approach that analyzes the effect size or event duration in its criticality assessment, even though such information would be needed to make profound statements regarding the anticipated risks (Frenzel et al. 2017). Third, Ioannidou et al. (2019) highlight negligence of temporal changes and site-specific characteristics in criticality assessment as most approaches are site generic and provide only a snapshot in time of supply and demand balances. In this context, Schrijvers et al. (2020b) add that it is sometimes even not clear at which point in time the risks of supply disruptions are analyzed because the included indicators refer to different time horizons.

2.2.4 Criticality indicators

Today, there is a consensus among the experts in the field of criticality assessment to perform the evaluation based on the supply disruption probability and the vulnerability by following Equation (4) (Cimprich et al. 2019; Frenzel et al. 2017; Schrijvers et al. 2020b).

$$Criticality = Supply\ disruption\ probability * vulnerability \tag{4}$$

These two criticality dimensions are represented with different indicators. Indicators for supply disruption probability are used to either describe a specific supply disruption event or define background reasons for a supply disruption. In the EC approach, for example, *geopolitical instability* is used to represent the event of domestic conflicts and aggressions caused by political unrest. A measure of low *diversity of supply/import* is used instead to refer to the circumstance of few supply alternatives, which incentivizes supply disruption in the existence of an event (European Commission 2017a). Note that *diversity of supply/import* is sometimes also considered as an event itself by associating a monopoly situation with a high probability of supply disruption (Graedel et al. 2012).

Indicators for vulnerability inform regarding the potential supply disruption impacts on the system under study (Helbig et al. 2016a). The use of these indicators thus depends on the type of impacts that are considered. According to Helbig et al. (2016a), indicators regarding the economic input value of supply chain processes are used to estimate changes in costs due to increased material prices, while indicators regarding the economic output value of a process (i.e. the revenue) are used as an approximation of the physical unavailability of materials for the process. Furthermore, Helbig and colleagues (2016) explain that the choice of indicators depends on whether the importance of materials is interpreted from an economic, a strategic or a technological perspective (see explanations of the different perspectives in section 2.2.1). Examples given by Helbig et al. (2016a) suggest that economic importance can be evaluated by the utilized material value or the economic feasibility of substitution, strategic importance can be assessed by the ratio of future demand to current production rates and technological importance can be evaluated by technical issues regarding material substitutability.

Schrijvers et al. (2020b) have performed an extensive review of existing criticality assessment approaches, in which they have identified the indicators for supply disruption probability and vulnerability used in these approaches. The indicators that are most frequently used in criticality assessment approaches reviewed by Schrijvers et al. (2020b) (i.e. used by more than 10% of the approaches) are listed in Figure 8. The frequency of use and the related types of systems under study for each indicator are specified with circles in Figure 8. Figure 8 clusters the indicators into short-term (on the top) and medium-term (on the bottom) indicators as well as indicators suitable for an evaluation over both time horizons (in the middle).

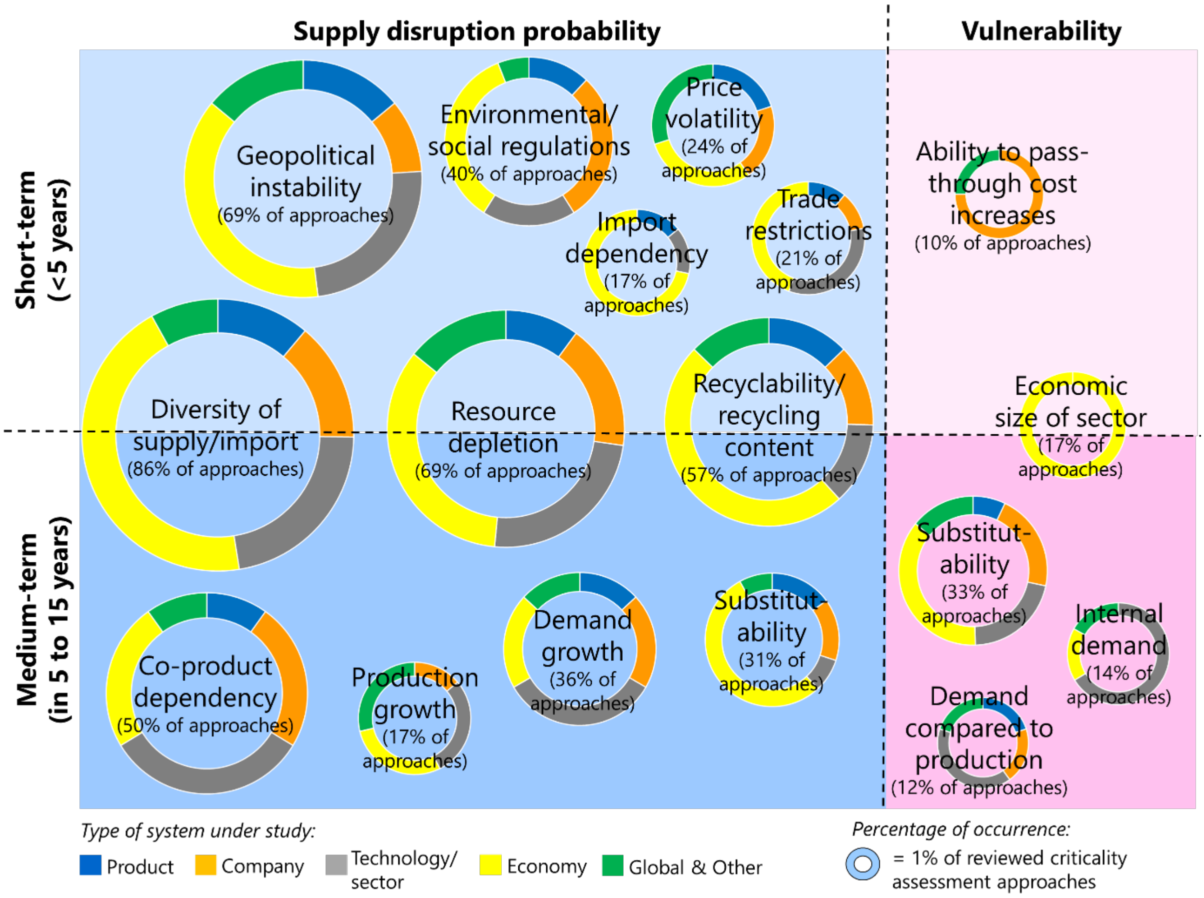

Figure 8: Commonly used supply disruption probability and vulnerability indicators considered in more than 10% of the approaches reviewed by Schrijvers et al. (2020b). Additionally, the frequency of use, the type of system and the relevant time horizon are visualized related to each of the indicators. Information about the frequency of use and the types of systems are taken from Schrijvers et al. (2020b) and the clustering into time horizons is done based on information from Erdmann et al. (2011) and Ku et al. (2018). The two considered time horizons are defined by following the proposition of Erdmann and Graedel (2011) and Graedel and Reck (2016). Modified illustration of Figure 4 from Schrijvers et al. (2020b).

Based on Figure 8, the following conclusions are drawn regarding the use of indicators in criticality assessment:

First, considering the sizes of the circles visualized in Figure 8, *diversity of supply/import*, *geopolitical instability*, *resource depletion* or *recyclability/recycling content*[2] are the most frequently considered issues in the evaluation of supply disruption probability. *Substitutability*, *economic size of sector* and *internal demand* are, in turn, the major concerns regarding an evaluation of vulnerability.

Second, Figure 8 shows by the example of substitutability that some indicators can be used for the analysis of both, supply disruption probability and vulnerability (Schrijvers et al. 2020b). The issue described with the indicator is then differently interpreted. Substitutability for example can either describe the possibility to reduce the likelihood of supply disruption by lowering the demand for a

[2] In this thesis, *recycling content* is also referred to as *primary raw material reliance* following explanations of Helbig et al. (2021).

specific material or refer to less severe consequences of a supply disruption in case of feasible substitution options (Helbig et al. 2016a).

Third, the sizes of the circles displayed in Figure 8 highlight that indicators for supply disruption probability are more frequently considered than vulnerability indicators. One reason is the differences in the requirements for the evaluation of supply disruption probability and vulnerability. The vulnerability can usually be described with a few indicators specific to the system under study, while the supply disruption probability needs to be evaluated based on several indicators because often various supply disruption events are expected. Approaches that utilize a variety of probability indicators and only a few vulnerability indicators are the NEDO approach (Hatayama and Tahara 2015) and the ESSENZ approach (Bach et al. 2016). Another reason is the omission of vulnerability indicators in some approaches such as in the one developed by BGS (2015).

Fourth, the color-coding of the circles shown in Figure 8 suggests that the use of vulnerability indicators correlates with the system under study. For example, the *economic size of sector* is only analyzed in relation to economies and the *ability to pass-through cost increases* is only considered on a corporate and global level. Such relation is also apparent in the Yale approach (Graedel et al. 2012), where for example the *net import reliance* is considered on a national level but not on a corporate or global level. Indicators for supply disruption probability in turn seem to be used independently from the type of system under study. Indeed, these indicators are usually mainly selected based on the consideration of supply disruption events (Hatayama and Tahara 2018).

Fifth, the differentiation into time horizons in Figure 8 shows that indicators are developed and applied for both, short- and medium-term assessments. Most of the indicators are relevant in the short- **or** medium-term time horizon. Indicators related to changes in the market for example caused by geopolitics, policies or price variations affect supply and demand balances in the next few years and are thus, relevant in the short-term. In contrast, indicators related to changes in resource availability, which may for example occur due to the growing demand/production amounts, the limited possibility of substitute implementation or the decreasing fabrication amounts of co-products, are relevant in the medium-term. A few indicators are relevant in the short- **and** medium-term. An example is *resource depletion*, where the relevant time horizon depends on whether economic resources or ultimate resources[3] are considered (Graedel et al. 2012). Other examples are the *diversity of supply/import*, *recyclability/recycling content* and *economic size of sector*. The relevant time horizons of these three indicators have been estimated by Ku et al. (2018) as 1 to 10 years, a time frame that extends over the short- and medium-term time horizons.

[3] According to Schneider et al. (2011), economic resources, also called reserves, are those that are economically extractable today and ultimate resources, also called reserve base, are those that are fulfilling chemical and physical criteria for extraction but are not economically extractable today.

The information regarding the use of criticality indicators provided above are inevitably based on the bias of experts designing of the criticality assessment approaches or estimating the time horizons. However, this information can be helpful to identify desirable, already widely considered as well as so far underrepresented indicators for the creation of new criticality assessment approaches.

The indicators for supply disruption probability and vulnerability can be quantified in different ways as shown in the reviews of indicator measurements conducted by Achzet and Helbig (2013) and Helbig et al. (2016a). Over the course of time, some quantification options have been regularly adapted and new ones have been proposed. In the ESSENZ approach (Bach et al. 2016), for example, the diversity of supply is quantified with the Herfindahl-Hirschman Index[4] (HHI) (Herfindahl 1950; Hirschman 1945), which is already used in the Yale approach, while the probability of trade restrictions is measured by the Enabling Trade Index (World Economic Forum 2016), a quantification option newly introduced to criticality assessment.

Table 1a and b demonstrate commonly considered quantification options for the supply disruption probability and vulnerability indicators described in Figure 8. These quantification options are primarily identified from the frequently used or adapted approaches listed in Figure 6 (i.e. the NRC, Yale, EC[5] and NEDO approaches). The indicators *trade restrictions*, *internal demand* and *demand compared to production* listed in Figure 8 are however not considered in these four approaches. Sample measurements for these indicators are thus collected from the ESSENZ approach (Bach et al. 2016) and the SCARCE approach (Bach et al. 2017b). We consider these two approaches relevant to the field of criticality assessment as they have already been included in prominent review studies such as the ones of Cimprich et al. (2019) and Schrijvers et al. (2020b) as well as applied in different case studies (Arendt et al. 2020; Sun et al. 2021).

[4] The Herfindahl-Hirschman Index is defined by the sum of the squares of the shares for each supplier (Herfindahl 1950; Hirschman 1945).
[5] Note that the methodology of the EC approach has been regularly updated over the last years and thus, indicators included in the latest methodology of the EC approach, i.e. the one described by the European Commission (2017b), have been considered.

Table 1: Definition of criticality indicators
considering indicators for a) supply disruption probability and b) vulnerability described in Figure 8. The measurements used in the NRC approach (NRC 2008), the EC approach (European Commission 2017a), the Yale approach (Graedel et al. 2012) and the NEDO approach (Hatayama and Tahara 2015) or, when necessary, in the ESSENZ approach (Bach et al. 2016) or the SCARCE approach (Bach et al. 2017b) are considered as examples.

(a) Indicators for supply disruption probability

Indicator	Measurement	Related approach
Diversity of supply/import	Herfindahl-Hirschman Index[4] (Herfindahl 1950; Hirschman 1945)	Yale approach
	Share of the country in the global supply	EC approach
	Share of the top production country	NEDO approach
	Share of the top import country	
	Share of the top resource-holding country	
Resource depletion	Ratio of reserve base* to global production	NRC approach
	Reserve* or reserve base* minus the raw material demand and the material losses from extraction and plus the life cycle distribution of a resource multiplied with the end-of-life recycling rate	Yale approach
	Ratio of reserves* to global production	NRC approach, NEDO approach
Geopolitical instability	Worldwide Governance Indicators[6] (World Bank 2019)	EC approach
	Worldwide Governance Indicator: Political Stability and Absence of Violence/Terrorism (World Bank 2019)	Yale approach
Recyclability/ recycling content	Qualitative evaluation based on a ratio of old scrap and demand	NRC approach
	Percentage of national secondary raw material content of the national production amount	EC approach
	Qualitative evaluation of recycling opportunities	NEDO approach
By-product dependency	Percentage of global production as co-product	NRC approach, Yale approach
Environmental/ social regulations	Policy Performance Index (Yunis and Aliakbari 2021) and Human Development Index (UNDP 2019)	Yale approach
Demand growth	Ratio of current annual demand to annual demand 10 years in the past	NEDO approach

[6] The Worldwide Governance Indicators comprise six different indicators including indicators for voice and accountability, political stability and absence of violence/terrorism, government effectiveness, regulatory quality, rule of law and control of corruption (World Bank 2019)

Table 1a (continued)

Indicator	Measurement	Related approach
Substitutability	Semi-quantitative evaluation of depletion potential, criticality and co-product dependency of substitute	EC approach
Price volatility	Ratio of highest to lowest price throughout 10 years	NEDO approach
Trade restrictions	Enabling Trade Index (World Economic Forum 2016)	ESSENZ approach (Bach et al. 2016)
Import dependency	Ratio of net imports to apparent consumption	NRC approach, EC approach
Production growth	Ratio of current annual production to annual production 10 years in the past	NEDO approach

*Reserves refer to resources that are economically extractable today; reserve base refers to resources that are fulfilling chemical and physical criteria for extraction but are not economically extractable today

(b) Indicators for vulnerability to supply disruption

Indicator	Measurement	Related approach
Substitutability	Qualitative evaluation of substitutable product share	NRC approach
	Qualitative evaluation of substitute performance and availability; Ratios of environmental impact, price and import reliance between substitute and raw material	Yale approach
	Semi-quantitative evaluation of substitute cost performance	EC approach
Economic size of sector	Qualitative evaluation	NRC approach
	Share of end-use of a raw material in an economic sector	EC approach
Internal demand	Imported amount	SCARCE approach (Bach et al. 2017b)
Demand compared to production	Ratio of amount of raw material used in the product system to global production amount	ESSENZ approach (Bach et al. 2016)
Ability to pass-through cost increases	Qualitative evaluation	Yale approach

Table 1 shows that quantitative data and qualitative evaluations are used to quantify the indicators for supply disruption probability and vulnerability. The comparison of Table 1a with Table 1b indicates that qualitative indicators are overall more frequently used for analyzing vulnerability than for analyzing supply disruption probability. Reasons for the use of qualitative indicators are mostly not specified. One reason may however be that judgment of experts is perceived as most suitable to define the system-specific vulnerability because they are the ones most familiar with the system under study. Other reasons may be a lack of data, time, money and personnel to perform data-intensive quantitative assessments. Some approaches prefer the use of quantitative indicators. An example is the EC approach, where almost no qualitative expert judgment is used to evaluate the considered indicators. Indeed, as highlighted by Schrijvers et al. (2020b), especially public studies utilize quantitative indicators to provide assessments perceived as being more objective. Furthermore, these types of studies generally favor the use of publicly available data because it allows for generating reproducible and transparent results and the assessments are thus defendable against criticism regarding the reflection of expert biases (Schrijvers et al. 2020b).

To advance the creation of reproducible and transparent results in criticality assessment, efforts have been made to provide quantitative indicators. For example, UNEP (2011) and Graedel et al. (2015) present quantitative descriptions of recyclability and substitutability, two indicators that have often been qualitatively evaluated in the past as shown in Table 1.

2.2.5 Aggregation of indicators

As shown in Figure 7, the indicators used in criticality assessment approaches are generally aggregated in one way or another to calculate the final criticality scores. Possible ways of indicator aggregation are explained in Schrijvers et al. (2020b). One way is the aggregation of sub-indicators to a composite single score indicator. An example is the aggregation of the six Worldwide Governance Indicators into an overall indicator as done in the EC approach. Another way is the aggregation of various indicators on the level of a specific dimension. This form of aggregation, which is supposedly the most common one, is applied in all four approaches described in Figure 6. In the NRC, EC and Yale approach, the respective indicators are aggregated to supply disruption probability and vulnerability dimensions. In the NEDO approach, the indicators are aggregated on the level of five dimensions including *supply risk*, *price risk*, *demand risk*, *recycling restrictions* and *potential risk*. A third way of aggregation is to summarize different dimensions into a single criticality score. In the NEDO approach, for example, the scores for the five different dimensions are aggregated into a single score for each raw material. These three ways of indicator aggregations are generally used in criticality assessment approaches to identify supply bottlenecks on the level of specific raw materials.

A fourth way of indicator aggregation is the calculation of a single criticality score for a whole product by aggregating the criticality scores of the raw materials included in the product. This way of aggregation is useful when comparing supply disruption impacts between different technologies. Helbig et al. (2016b, 2018) have for example applied such an aggregation to compare CdTe vs. CIGS thin-film photovoltaics and different lithium-ion battery cell technologies. However, other approaches suggest that aggregation on the product level is not necessary for such comparisons. According to the interpretation of Mota et al. (2017), the overall criticality for bulk metallic glasses is described by the highest criticality score among all the included bulk metallic glass constituent materials. Helbig et al.

(2016b, 2018) also consider this interpretation as a second option to compare the overall supply disruption impacts between different thin-film photovoltaics or lithium-ion battery cell technologies.

2.2.6 Environmental and social implications

According to Schrijvers et al. (2020b), environmental and social impacts considered within criticality assessment approaches are analyzed from one of the following four perspectives.

The first perspective refers to a probability of supply disruption caused by the implementation of environmental or social regulations that restrict mining or production practices. This perspective is considered in the approach of the European Commission (2010) or the Yale approach (Graedel et al. 2012), where the said probability is evaluated using the Environmental Performance Index (Wolf et al. 2022) and the Policy Performance Index (Yunis and Aliakbari 2021), respectively.

The second perspective refers to a rating of materials as critical when their use has a high impact on the environment or society. The Yale approach (Graedel et al. 2012) considers this perspective by analyzing the impacts on the ecosystems and human health based on the LCIA method ReCiPe 2008 (Mark Goedkoop et al. 2009). Graedel and colleagues (2012) evaluate these impacts within a third dimension next to the supply disruption probability and vulnerability dimensions. The ÖkoRess method developed by Kosmol et al. (2018) and applied to seven different raw materials by Manhart et al. (2019) evaluate these impacts even more prominently in their study by considering them as the only dimension besides vulnerability.

The third perspective refers to the evaluation of the impact related to a disrupted material flow on the environment or society. This perspective has been explained by Frenzel et al. (2017) for the example of the potential impacts of deep-sea mining that may become profitable in case of a further rise in raw material prices. However, this perspective has not been analyzed in any of the well-known criticality assessment approaches.

The fourth perspective refers to the evaluation of reputational risks, which occur when materials with high environmental or social impacts are used by organizations and thus trade partners refuse to engage with these organizations. The RESCHECK tool (Spörri et al. 2017) for example evaluates reputational risks based on the impacts of materials/products on Human Health and Ecosystems using the LCIA method ReCiPe 2008 (Mark Goedkoop et al. 2009) as well as on the society using a qualitative evaluation of conflict potentials and the Corruption Perception Index (Transparency International 2023).

These four perspectives are used and interpreted differently within criticality assessment approaches. The first perspective refers to probabilities that are evaluated within the framework of criticality assessment described by Equation (4). The second perspective refers to impacts usually assessed in the LCIA phase within LCA or SLCA studies. While these impacts are relevant for the analysis of the environmental and social pillars within a sustainability assessment, they do actually not indicate whether the use of a material/product is associated with high or low risk. The third perspective refers to impacts on the environment and society that have so far been rarely considered in the field of criticality assessment. Similar to the impacts considered in the second perspective, these impacts should be evaluated within the environmental or social pillars within a sustainability assessment. Reputational risks described with the fourth perspective represent an additional impact to cost variability and limited availability, the two impacts commonly analyzed in criticality assessment (see section 2.2.2). Following Schrijvers et al. (2020b), reputational risks are mainly evaluated in studies designed for companies.

2.3 Criticality assessment within Life Cycle Sustainability Assessment

Some approaches that assess the criticality of raw materials have been integrated into the LCA and LCSA frameworks (Cimprich et al. 2019; Sonnemann et al. 2015). Different authors advocate for the assessment of criticality as a complement to LCA within the broader LCSA framework because supply disruption impacts go beyond the environmental impacts that are in the focus of traditional LCA studies (Dewulf et al. 2015b; Drielsma et al. 2015; Sonnemann et al. 2015). The motivations and benefits for such an integrated assessment are explained in section 1.3.

Cimprich and colleagues (2017, 2019) pointed out that there are fundamental differences between the methods that assess criticality within LCSA and the LCIA methods that are used within LCA studies. Conventional LCIA methods consider only "inside-out" relations, where internal processes within a product system are causing impacts on the environment. Such an "inside-out" perspective focuses on the environmental impacts of elementary flows (i.e. exchanges between a product system and the environment in form of emissions and resource consumption). Conversely, criticality assessment within an LCSA framework is based on "outside-in" relations, where the impacts caused by the changes of external conditions (e.g. a decrease in supply or changes in demand) inform on supply disruptions that affect the product system. The "outside-in" assessment methods thus require not only the consideration of elementary flows but also the analysis of process flows (i.e. materials and energy flows between the processes of a supply chain) to evaluate the supply disruption impacts.[7]

In 2019, Cimprich and colleagues have published the latest review regarding the state-of-the-art of approaches integrating criticality assessment into the LCSA framework (Cimprich et al. 2019). Their review covers the approaches highlighted in blue in Table 2. Table 2 summarizes the approaches included in the review publication of Cimprich et al. (2019) (highlighted in blue) and additional approaches (highlighted in white).

[7] As the focus in this thesis is on an analysis of supply risks along the full supply chain integrated into the LCSA framework, elementary flows and process flows are collectively termed "inventory flows" in the rest of the document, analogously to Cimprich et al. (2019).

Table 2: Overview of existing approaches
integrating criticality assessment into the LCSA framework. The approaches highlighted in blue have been covered in the review of Cimprich et al. (2019).

Approach	**year**	**Title**	**Contribution**
ESP approach (Schneider et al. 2013)	2013	The economic resource scarcity potential (ESP) for evaluating resource use based on life cycle assessment	Development of an approach assessing different impacts affecting the economic availability of metallic raw materials complementary to existing environmental LCIA methods
GeoPolRisk approach (Gemechu et al. 2015b)	2015	Import-based Indicator for the Geopolitical Supply Risk of Raw Materials in Life Cycle Sustainability Assessments	Inclusion of geopolitical and import-based indicators within the LCSA framework to address besides the geological availability also the geopolitical supply situation of raw materials
ESSENZ approach (Bach et al. 2016)	2016	Integrated method to assess resource efficiency - ESSENZ	Development of a life cycle based approach to determine socio-economic availability of abiotic resources, metals and fossil raw materials together with environmental impacts and societal acceptance of raw materials supply
Supply chain extension of the GeoPolRisk approach (Helbig et al. 2016c)	2016	Extending the geopolitical supply risk indicator: Application of life cycle sustainability assessment to the petrochemical supply chain of polyacrylonitrile-based carbon fibers	Extension of the GeoPolRisk indicator by considering domestic production and assessing multiple supply chain stages
BIRD approach (Bach et al. 2017a)	2017	Assessing the Availability of Terrestrial Biotic Materials in Product Systems (BIRD)	Development of an approach based on ESSENZ to determine the socio-economic availability of biotic materials and their related intermediate and final products
SCARCE approach (Bach et al. 2017b)	2017	Enhancing the assessment of critical resource use at the country level with the SCARCE method – Case study of Germany	Development of an approach based on ESSENZ to assess the impacts related to the use of critical metals and fossil fuels at the country level
Extended GeoPolRisk approach considering a characterization model (Cimprich et al. 2017)	2017	Extension of geopolitical supply risk methodology: Characterization model applied to conventional and electric vehicles	Extension of the GeoPolRisk approach by the creation of an LCIA characterization model for evaluating geopolitical supply risk of raw materials related to a functional unit within the LCSA framework

Table 2 (continued)

Approach	year	Title	Contribution
Extended GeoPolRisk approach considering substitutability (Cimprich et al. 2018)	2018	Extending the geopolitical supply risk method: material "substitutability" indicators applied to electric vehicles and dental X-ray equipment	Extension of the GeoPolRisk approach by incorporating the risk-mitigating effect of material "substitutability"
Extended GeoPolRisk approach considering an endpoint indicator (Santillan et al. 2020)	2020	Design of an endpoint indicator for mineral resource supply risk in life cycle sustainability assessment - The case of Li-ion batteries	Extension of the GeoPolRisk approach by an endpoint indicator that allows to assess the socio-economic damage of mineral resource use
Extended GeoPolRisk approach considering supply risk mitigation of recycling (Santillán-Saldivar et al. 2021)	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	Extension of the GeoPolRisk approach by an analysis of the risk-mitigating potential of domestic recycling considering reduction in imports and potential redistribution of imports
EPI approach compatible with approaches such as GeoPolRisk, ESP or ESSENZ (Lütkehaus et al. 2022)	2022	Measuring raw-material criticality of product systems through an economic product importance indicator: a case study of battery-electric vehicles	Introduction of the 'economic product importance' (EPI), an indicator to measure the relevance and significance of raw materials that is compatible with existing evaluations of supply disruption probability

The developments of criticality assessment approaches within LCSA can be divided into two branches. One refers to the development of the GeoPolRisk approach and the other one refers to the development of the ESSENZ approach, which is a successor of the prior developed ESP approach.

The development of the GeoPolRisk approach has been initialized by Sonnemann et al. (2015), who suggested a framework for the integration of an impact assessment for geopolitical supply disruption into the LCSA framework. Gemechu et al. (2015b) have then developed an import-based indicator for geopolitical supply disruption probability, which has been extended by a supply chain perspective (Helbig et al. 2016c). Cimprich et al. (2017) have transformed the original relative GeoPolRisk Indicator into an LCIA characterization model for GeoPolRisk that includes supply disruption probability and vulnerability indicators. Building upon the development of this characterization model, the GeoPolRisk approach has been extended by considering substitutability as a vulnerability indicator (Cimprich et al. 2018), by designing an endpoint indicator to measure the socio-economic damage (Santillan et al. 2020) and by assessing the risk-mitigation potential of domestic recycling (Santillán-Saldivar et al. 2021). During these developments, the GeoPolRisk approach has been tested in several case studies including electric vehicles (Cimprich et al. 2017; Gemechu et al. 2015a), polyacrylonitrile-based carbon fibers (Helbig et al. 2016c), dental X-ray equipment (Cimprich et al. 2018), batteries (Koyamparambath et al. 2022; Santillan et al. 2020; Santillan Saldivar et al. 2022) and helium (Siddhantakar et al. 2023).

Building upon the ESP approach (Schneider et al. 2013), Bach et al. (2016) have developed the ESSENZ approach, where different impact categories related to the socio-economic availability of materials and resources are considered together with environmental impacts and societal acceptance. Based on the ESSENZ approach, Bach et al. (2017a) have proposed the BIRD approach, which allows for evaluating the socio-economic availability of biotic materials and related products at different stages of the supply chain, and Bach et al. (2017b) have designed the SCARCE approach, which enables to assess critical resources use for a country by considering its imports. Sun et al. (2021) have applied the ESSENZ approach in a case study of passenger vehicles and Arendt et al. (2020) have used the SCARCE approach in a criticality assessment of abiotic raw materials used in Europe.

Lütkehaus et al. (2022) have focused on advancing the evaluation of vulnerability by introducing the vulnerability indicator 'economic product importance' (EPI). This indicator allows for evaluating the relevance and significance of a raw material used in a product system. As argued by the authors, their vulnerability indicator is designed to be compatible with the evaluation of supply disruption potential in the ESP, ESSENZ and GeoPolRisk approaches. To illustrate the functionality of their newly developed indicator, Lütkehaus et al. (2022) have tested it in combination with the GeoPolRisk Indicator developed by Gemechu et al. (2015b) in a case study of battery electric vehicles.

In general, the approaches listed in Table 2 assess supply disruption impacts similar to the LCIA in LCA by multiplying a flow of raw material with its respective CF. These CFs comprise supply disruption probability and vulnerability indicators (Equation (5)). Exceptions are the approaches developed by Gemechu et al. (2015b) and Helbig et al. (2016c), where CFs include a probability indicator but miss a vulnerability indicator. These CFs thus describe relative supply disruption probabilities and not the actual risk of supply disruption for the product system as defined by Glöser et al. (2015).

$$\begin{gathered} Supply\ disruption\ impact = m * CF \\ CF = supply\ disruption\ probability * vulnerability \end{gathered} \tag{5}$$

While the developments of the GeoPolRisk and ESSENZ approaches are equal in their calculation structures, the definition of supply disruption probability and vulnerability differs between the two approaches. To illustrate the differences in the respective impact assessments, calculations of impact scores for geopolitical supply disruption (*GPSDI*) are shown in Equation (6) for the GeoPolRisk approach considering the extended approach of Cimprich et al. (2017)[8] and in Equation (7) for the

[8] Out of the different extensions of GeoPolRisk, the GeoPolRisk approach extended by Cimprich et al. (2017) is considered for demonstrating the impact assessment with GeoPolRisk because it describes an important development regarding the assessment of the actual impacts and not only the probabilities of supply disruptions.

ESSENZ approach (Bach et al. 2016). The fictional example of a raw material *A* produced in country *i* and used in a product *P* in country *c* is thereby considered. The green and orange colors used in Equations (5), (6) and (7) indicate which indicators are used to analyze supply disruption probability (i.e. green) and which are used for vulnerability analysis (i.e. orange), respectively.

Extended GeoPolRisk approach considering a characterization model (Cimprich et al. 2017):

$$GPSDI_{APc} = m_{APc} * CF_{APc}$$

$$CF_{APc} = HHI_A * \sum_i \left(WGI(PS)_i * \frac{import_{Aic}}{production_{Ac} + import_{Ac}} \right) * \frac{1}{m_{APc}} \tag{6}$$

or

$$CF_{APc} = HHI_A * \sum_i \left(WGI(PS)_i * \frac{import_{Aic}}{production_{Ac} + import_{Ac}} \right) * EI_{A/Wc}$$

ESSENZ approach (Bach et al. 2016):

$$GPSDI_A = m_A * CF_A$$

$$CF_A = \sum_i \left(\left(\frac{WGI_i}{target_{WGI}} \right)^2 * \frac{production_{Ai}}{production_{A,GLO}} \right) * \frac{1}{production_{A,GLO}} \tag{7}$$

To evaluate the supply disruption potential in the GeoPolRisk approach as described in Equation (6), geopolitical instability and production concentration is considered. The production concentration is defined with the *Herfindahl-Hirschman Index (HHI)* of production countries and the geopolitical instability is determined based on the *Worldwide Governance Indicator-Political Stability and Absence of Violence/Terrorism (WGI(PS))* weighted by the import shares of the individual trade partners, considering additionally the risk mitigation of domestic production. To evaluate vulnerability, Cimprich et al. (2017) propose two different embodiments. One applies a product-level importance factor ($\frac{1}{m_{APc}}$) assuming that all inputs to the product system are equally important. The other one adapts the methodology of Chapman et al. (2013) by measuring economic importance of the material at an *economy-wide* level, normalized to tungsten as a reference material ($EI_{A/Wc}$).

To evaluate the supply disruption potential in the ESSENZ approach as described in Equation (7), the geopolitical instability is determined based on the average of the six *Worldwide Governance Indicators (WGIs)* weighted by the global production shares and divided by a target value for the geopolitical instability ($target_{WGI}$) defined by expert judgment. This so-called distance-to-target value consisting of the country-specific WGI value and the $target_{WGI}$ value is squared in order to weight major exceedance of the target value above-proportionally (see the *Ecological Scarcity Method Eco Factors 2006* proposed by Frischknecht et al. (2009)). To evaluate vulnerability, the flow amount of the material is normalized by its corresponding global production.

From the calculations of impact scores described in the Equations (6) and (7), it can be concluded that objectives of the GeoPolRisk and ESSENZ approaches differ significantly. The approaches related to GeoPolRisk aim to assess supply disruption impacts for a downstream manufacturing country based on its trade relationships with upstream raw material supplying countries. The ESSENZ approach, in turn, aims to provide global-level CFs that allow for evaluating supply disruption impacts of raw materials used in multinational companies or organizations.

2.4 Criticality assessment of the Swiss economy

Swissmem, the association of the Swiss mechanical, electrical and metal production industry (MEM-industry), has performed the first criticality study for the Swiss economy in 2010 (Kohl 2010). In this study, a survey among its 1000 member companies has been conducted with the aim to investigate to what extent critical raw materials are used in this industry branch. The companies have been asked whether they use critical raw materials directly or indirectly (i.e. in form of intermediate products). For that purpose, the 17 raw materials listed in Figure 9 have been predefined by the organizers of the survey (Kohl 2010). The outcomes of the survey visualized in Figure 9 indicate a high reliance of the MEM-industry on critical raw materials because they show that around 75% of the responding companies use at least one of these raw materials.

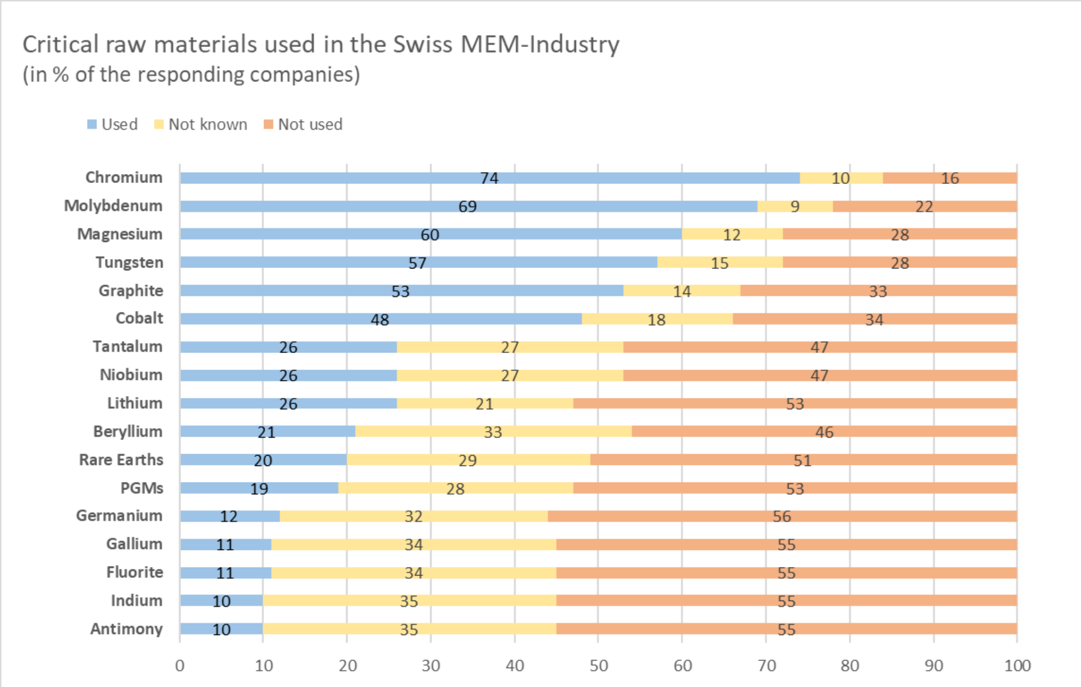

Figure 9: Results of the criticality study performed by Swissmem
for the Swiss mechanical, electrical and metal production industry (MEM-Industry). Figure adapted and translated from Kohl (2010).

Empa, in collaboration with Ernst Basler + Partner AG, has conducted a second criticality study for the Swiss economy on the level of three small and medium-sized enterprises (SME) (Spörri et al. 2017). In their study, the so-called RESCHECK tool (RESourcenCHECK tool) was developed, a tool for SME to estimate their resource dependency and to develop risk mitigation and innovation strategies related to the supply of critical metals (Spörri et al. 2017). RESCHECK allows for analyzing supply disruption probability and vulnerability of metals and intermediate/final products. The indicators *geological abundance*, *country supply concentration*, *co-product dependency*, *global demand development* and *price volatility* are considered to define supply disruption probability. The indicators *strategic importance*, *substitutability* and *ability to innovate* are considered to define vulnerability. All indicators are evaluated on a scale from 1 (i.e. very low criticality) to 5 (i.e. very high criticality). The thus defined levels of criticality are specified with individual thresholds for each of the indicators. Quantitative data are used for evaluating supply disruption probability indicators and expert judgment is used for evaluating vulnerability indicators. The criticality assessment with RESCHECK includes 35 metals that have been selected from the Swissmem study and from the list of critical raw materials published by the European Commission (2014).

The tool has been tested on three pilot SMEs comprising a company producing electrical drive and controller technologies, a company producing bearingless pumps and a company producing flexible thin-film photovoltaics. The metals and intermediate/final products that are used in the respective companies and included in the tool are considered for the evaluation. The results of this trial are represented in Table 3.

Table 3: Results of the criticality study performed by Empa evaluating supply disruption probability and vulnerability for three Swiss small and mid-size enterprises (SME). Supply disruption probability is evaluated based on geological abundance (GA), country supply concentration (CC), co-product dependency (CD), global demand development (DD), price volatility (PV) and the average of scores for these five indicators (Prob). Vulnerability is evaluated based on strategic importance (SI), substitutability (SU), ability to innovate (IA) and the average of the scores for these three indictors (Vul). The scale from 1 to 5 indicate with *1* a very low criticality and with *5* a very high criticality. Own depiction based on Spörri et al. (2017).

Metals and intermediate/final products	**Supply disruption probability**						**Vulnerability**			
	GA	CC	CD	DD	PV	**Prob**	SI	SU	IA	**Vul**
Pilot-SME 1: Company producing electrical drive and controller technologies										
Magnet (engine)	3	5	4	5	4	**4**	5	2	4	**4**
Dysprosium	3	5	4	5	4	**4**	5	2	4	**4**
Neodymium	3	5	4	4	4	**4**	5	2	4	**4**
Programmable logic controller & human-machine-interface	4	5	4	5	3	**4**	5	2	4	**4**
Antimony	4	5	4	1	3	**3**	5	2	4	**4**
Gallium	3	5	4	5	3	**4**	5	2	4	**4**
Indium	4	3	4	3	2	**3**	5	2	4	**4**
Molybdenum	3	3	3	3	2	**3**	5	2	4	**4**
Niobium	3	5	2	2	3	**3**	5	2	4	**4**
Tantalum	3	5	3	1	3	**3**	5	2	4	**4**
Pilot-SME 2: Company producing bearingless pumps										
Magnet (engine)	3	5	4	5	4	**4**	4	3	3	**3**
Dysprosium	3	5	4	5	4	**4**	4	3	3	**3**
Cobalt	3	5	4	4	3	**4**	4	3	3	**3**
Neodymium	3	5	4	4	4	**4**	4	3	3	**3**
Samarium	3	5	4	4	4	**4**	4	3	3	**3**
Pilot-SME 3: Company producing flexible thin-film photovoltaics										
Thin-film photovoltaics	4	5	4	5	3	**4**	4	5	3	**4**
Gallium	3	5	4	5	3	**4**	4	5	3	**4**
Indium	4	3	4	3	2	**3**	4	5	3	**4**

Overall, Table 3 shows that, on average, the supply disruption probability and vulnerability are moderate or high (i.e. score of 3 or 4) for all three companies. The scores of the indicators for supply disruption probability vary for the specific metals/products used within a company. This suggests that the supply disruption probability is for example higher for magnets, dysprosium or gallium than for indium, molybdenum or tantalum. Conversely, the scores of the vulnerability indicators do not differ for the metals/products used by a specific company. Thus, all metals/products have supposedly a similar economic and strategic relevance to the individual companies.

Similar evaluation patterns are seen for the three companies regarding the analysis of supply disruption probability. The *country supply concentration* is evaluated as the most critical indicator for most of the materials/products, which suggests that high amounts of the annual global production stem from politically instable countries. Furthermore, the co-product dependency and the global demand development are overall rated as critical, while lower probabilities of supply disruptions are expected in relation to geological abundance and price volatility.

Different evaluation patterns are seen for the three companies regarding the analysis of vulnerability. While all companies estimate a high to very high risk regarding the strategic importance and a medium to high risk regarding their ability to innovate, the evaluation of substitutability varies significantly among the three companies. The substitutability estimates range from a high ability to substitute in case of Pilot-SME 1 to a very low ability to substitute in case of Pilot-SME 3.

2.5 Research gaps

Within the two criticality studies performed for Switzerland (see section 2.4), four major shortcomings exist in relation to the central question of the on-hand thesis (i.e. what are potential supply disruption impacts along the global supply chains within the Swiss mobility, energy and ICT sectors?). First, the studies are performed on a corporate-level and only cover a limited number of companies, which does not allow for representing the supply disruption impacts for the considered sectors of the Swiss economy. Second, they significantly rely on expert judgment and are thus rather unsuitable for a government assessment because, as highlighted by Schrijvers et al. (2020b), it is particularly important for such assessments to avoid criticism regarding the reflection of expert biases. Third, the two studies consider only a few metals and/or intermediate/final products, which restricts the information about potential supply disruptions that can be provided along the supply chain. Finally, both studies do not allow for an assessment integrated into the LCSA framework and thus, miss the respective benefits (see a list of benefits in section 1.3).

In fact, section 2.3 represents approaches integrating criticality assessment within LCSA that could be applied in the context of the Swiss economy.

However, as highlighted by Cimprich et al. (2019), the possibilities to analyze multiple stages of supply chains are limited with existing approaches assessing criticality within LCSA, as mostly only raw material supply is analyzed in these approaches. Nevertheless providing an assessment that covers different stages of a supply chain is important because, as explained in section 1.2, supply disruption impacts are expected to occur in different parts of the global Swiss supply chains. Recent efforts by Helbig et al. (2016c) have extended the GeoPolRisk approach along a multi-stage supply chain, however this approach lacks a consideration of indicators that account for the vulnerability of a system and is not explicitly linked to the functional unit of the analyzed product, which is problematic because all impacts assessed within an LCSA should be related to a clear reference unit (see section 2.1.2). Other approaches like ESSENZ and BIRD (Bach et al. 2016, 2017a) also seek to consider different stages of a supply chain (e.g. resource extraction, raw material processing and downstream manufacturing processes). However, they have two significant limitations. First, they only focus on abiotic materials (e.g. cobalt) or biotic materials (e.g. natural rubber) and do not address both types of materials, which is problematic when supply risks for biotic and abiotic materials need to be analyzed and compared. Second, the approaches model processes of a supply chain without considering spatial specificities, which is problematic given the site-specific nature of supply disruption impacts (Ioannidou et al. 2019).

A second issue of existing approaches integrated into an LCSA framework is their focus on short-term events or lack of an explicit consideration of the temporal aspect, which makes it difficult to identify supply disruptions that have consequences beyond the short-term period. GeoPolRisk (Cimprich et al. 2017, 2018) disregards impacts from events in a medium-term and BIRD (Bach et al. 2017a) in turn does not offer an explicit consideration of the time horizon. In contrast, ESP (Schneider et al. 2013) and ESSENZ (Bach et al. 2016) do assess impacts in the short- or medium-term by considering inventory flows and indicators defined based on recent production amounts, however, these flows and indicators may not be relevant for medium-term events because production amounts might change in the coming years.

A third issue is that existing approaches assessing criticality within LCSA are often limited in their representation of supply disruption events and thus bear the risk of overlooking relevant supply risks. GeoPolRisk (Gemechu et al. 2015b), for example, only assesses impacts caused by geopolitical instability without considering other events that may cause supply disruptions.

A fourth issue is the lack of approaches integrated in an LCSA framework that allow for assessing criticality for entire sectors of an economy. Most of the existing approaches perform criticality assessments mostly only on the level of a specific product, which is problematic as potential supply disruption impacts for some of the relevant technologies used within the economy would be neglected in the decision-making. For example, GeoPolRisk extended by Cimprich et al. (2017, 2018) and the approach of Lütkehaus et al. (2022) evaluate the criticality of a specific product used in a country/region, while ESP, ESSENZ and BIRD (Schneider et al. 2013; Bach et al. 2016, 2017a) consider the use of a specific product in a multinational company. SCARCE (Bach et al. 2017b) instead performs an assessment on the economy-level. Their assessment considers the consumption of raw materials in the whole country. However, it does not provide information for specific sectors or technologies, which would be needed to make decisions crucial on technology or sectoral levels.

In conclusion, none of the currently existing approaches integrating criticality assessment into an LCSA framework is in fact suitable to assess short-term and medium-term supply disruption impacts along the global supply chains for the mobility, energy and ICT sectors within the Swiss economy.

"The amateurs discuss tactics: the professionals discuss logistics."

~ Napoleon Bonaparte

3. The SPOTTER approach

Globalization has boosted technological development around the globe but has also introduced some risks to the operation of global and interconnected supply chains. Just recently, several events including the Brexit, the China-USA trade war, the COVID-19 pandemic or the Russian-Ukrainian conflict have disrupted supply chains and thus majorly affected the global economy (Graham et al. 2020; OECD 2022). As explained in section 2.2, criticality assessment is a method that is suitable to evaluate potential supply disruption impacts over the next years or decades. Because sustainability assessment has also become increasingly relevant in terms of achieving sustainable development goals such as the decrease of GHG emissions, there is, as highlighted in section 1.3, a strong interest in integrating criticality assessment into the LCSA framework (Hackenhaar et al. 2022; Sonnemann et al. 2015). Through this integration, public administrations and companies can evaluate supply disruption impacts within a framework that is commonly used for decision-making regarding sustainable development. They are thus able to, amongst others, avoid burden shifting between environmental impacts and supply disruption impacts as well as between supply disruption impacts for different processes along the supply chain (see a description of motivations and benefits of such an integration in section 1.3).

However, as highlighted in section 2.5, the existing approaches integrating raw material criticality assessment into the LCSA framework do not comprehensively assess supply disruption impacts along the full supply chain and do not properly analyze short-term and medium-term supply risks with the same approach. There is therefore a high risk of neglecting potential supply disruption impacts that would actually affect the decision-making in public administrations and companies regarding resilient supply chain design.

Thus, this chapter aims at proposing a novel approach, further referred to as SPOTTER, which is assessing supply disruption impacts along the full supply chain in the short- and medium-term within the LCSA framework. We thereby investigate the following research question:

> ***RQ1*: How can potential supply disruption impacts be evaluated along full supply chains in the short- and medium-term within the Life Cycle Sustainability Assessment framework?**

This research question is further specified by the following four sub-research questions of this chapter:

- *Q1*: How can hotspot and overall impact scores for potential supply disruptions be calculated along the full supply chain within the Life Cycle Sustainability Assessment framework?
- *Q2*: Which short-term and medium-term events and impacts of potential supply disruptions are to be considered for the calculation of hotspot and overall impact scores?
- *Q3*: What are suitable indicators to represent the cause-effect chains between the considered events and impacts of potential supply disruptions?
- RQ4: What is a suitable procedure to simplify the assessment of potential supply disruption impacts along the full supply chain within the Life Cycle Sustainability Assessment framework?

This chapter is structured as follows: It begins with the definition of goals and concepts of the SPOTTER approach in section 3.1. Section 3.2 then provides an overview of elements for the impact assessment within the SPOTTER approach after first explaining the calculation procedures for related impact scores and CFs and then describing the procedure for the identification of required indicators. Section 3.3 is dedicated to the presentation of a possible procedure simplifying the application of the SPOTTER approach. At the end of the chapter, section 3.4 describes implications related to the use of the SPOTTER approach and provides a conclusion and perspective.

3.1 Goals and concepts of the SPOTTER approach

The SPOTTER approach is developed in order to address the issues of full supply chain coverage, spatiotemporal variability consideration and supply disruption event representation described in section 2.5. The goal of the SPOTTER approach is thus to provide a quantitative assessment of supply disruption impacts along the supply chain in the short- and medium-term complementing LCA as part of a broader LCSA framework. The assessments with SPOTTER allow then to identify the overall supply disruption impacts for the analyzed product systems and the supply disruption hotspots within the supply chain. Figure 10 describes the concepts of inventory analysis, impact assessment and interpretation that are applied for these assessments.

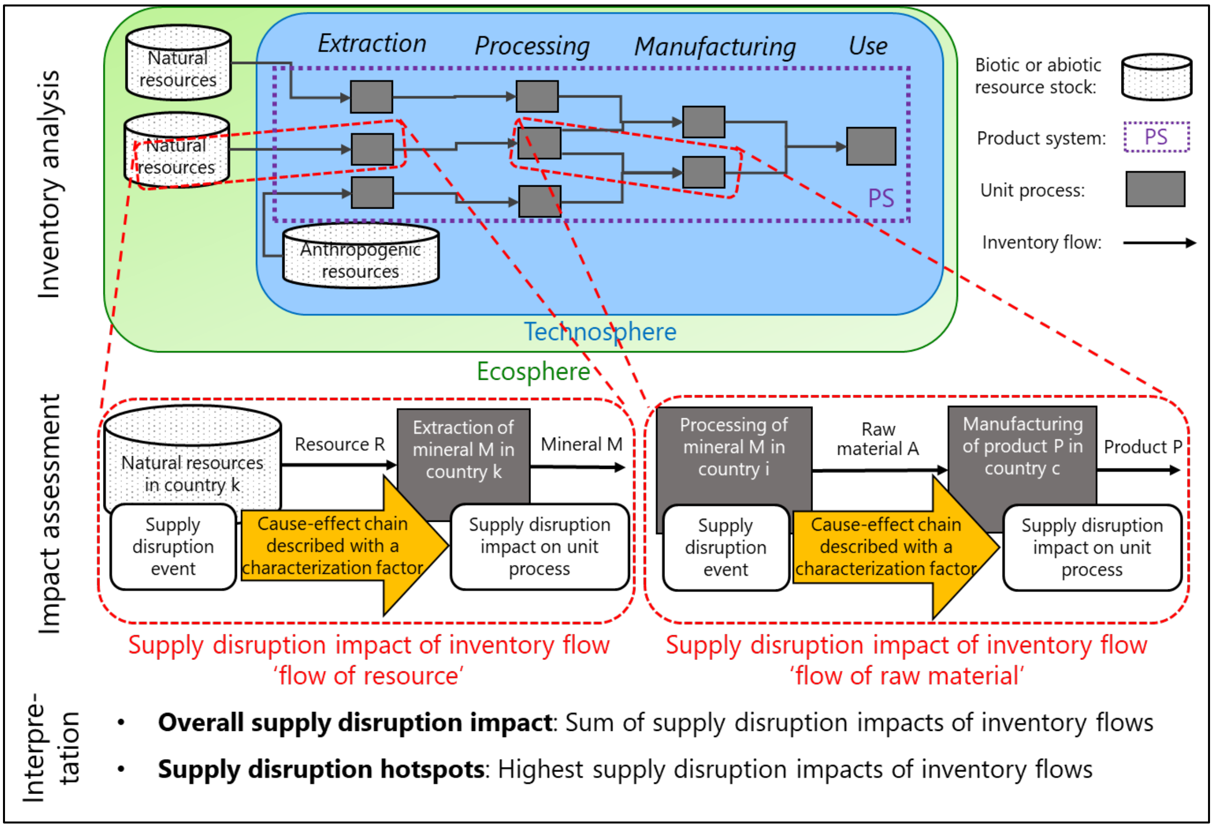

Figure 10: Conceptual schematic for the assessment with the SPOTTER approach

As illustrated in the top part of Figure 10, the inventory analysis of the SPOTTER approach considers all inventory flows of the supply chain models that are created in the inventory analysis step of the LCSA framework. These flows describe inputs and outputs of processes that are related to the functional unit of the product system. The considered processes define the stages of resource extraction, processing, manufacturing and use in the modeled system. These processes, which are in this chapter referred to as country-specific unit processes in the system, can take place anywhere around the world and are differentiated by the country in which they occur. The inventory flows connecting the unit processes represent amounts of minerals, raw materials, intermediate products and final products. The inventory flows originating from stocks of biotic or abiotic resources that can be found in the ecosphere or the technosphere represent the amounts of extracted resources. The supply chain models that are created for the LCSA framework present inventory flows that have occurred in the past, that are currently occurring and that will occur in the future. Only the inventory flows for the future are considered in the SPOTTER approach because only their potential supply disruption impacts are relevant to inform resilient design, precaution to be taken or risk mitigation.

In the stage of impact assessment in the LCSA framework, the SPOTTER approach is used to consider impacts caused by changes of conditions that are external to the modeled system (these changes are referred to as supply disruption events in this thesis). These "outside-in" impacts on all the country-specific unit processes are assessed individually for each inventory flow, as shown in the conceptual example presented in the middle part of Figure 10 where supply disruption impacts for flows of natural resource and raw material are evaluated. To define specific supply disruption impacts CFs that describe the cause-effect chains between the respective supply disruption event and impact are assigned to each inventory flow.

Following the explanations in the bottom part of Figure 10, the evaluation of overall supply disruption impacts and the hotspot analysis is performed as follows: The SPOTTER approach assesses the overall supply disruption impacts as the sum of impacts from all processes in the supply chain for different impact categories. The hotspots analysis refers to the identification of supply bottlenecks in the product system (Beer 2015; Mizgier et al. 2012). These bottlenecks follow the definition provided by Beer (2015): *"Locations where impediments arise to the normal functioning of a system"*. Considering this definition, the hotspot analysis is carried out by the evaluation of supply disruption impacts for all inventory flows in a supply chain and the flows associated with the highest impacts are considered as key supply bottlenecks (i.e. supply disruption hotspots).

In the SPOTTER approach, the relevant impacts for the short-term events are evaluated separately from the impacts that are only linked to the medium-term events so that practitioners can identify the appropriate responses at different time (possible response options to impacts in different time horizons are described by Ku et al. (2018)). Impacts in the short-term are assessed for inventory flows occurring within the next 5 years and impacts in the medium-term are assessed for the inventory flows occurring within the next 5 to 15 years. The quantification of inventory flows over both periods and the definition of CF values for each inventory flow constitutes two steps that are further explained in the section 3.2.3. The long-term perspective is not considered in the SPOTTER approach since quantitative information about impacts of potential supply disruptions that will happen in more than 15 years are linked to high uncertainties, which is especially the case in areas with fast technological change.

Different supply disruption events are considered for the short- and medium-term assessments. While events that describe frequent changes with immediate effects are analyzed in the short-term assessments, events that represent a progressive change with expected effects only in 5 to 15 years are relevant for the medium-term assessments. Clustering strategies for events with different time horizons have been provided by Ku et al. (2018) or Glöser et al. (2015).

Some supply disruption events are evaluated specific to countries, which means that flows of the same material/product between different countries will be evaluated differently with the SPOTTER approach. Conversely, other supply disruption events that are expected to have equivalent impacts around the world are evaluated on a global level. A list of examples for country-specific and global events is provided in Bach et al. (2017b).

According to Frenzel et al. (2017), the effects of supply disruption events are either *price hikes* or *severe physical disruptions*. The SPOTTER approach thus considers these two options in two different impact categories, which are *cost variability* and *limited availability*. The former refers to supply disruption events that may increase the prices of the supplied materials/products, which then leads to changes in costs for their production. The latter refers to supply disruption events that may reduce or remove access to input flows, which then results in limited availability of the output from processes included in the product system.

Schrijvers et al. (2020a) have pointed out that supply disruption impacts are associated with the economic damage on the supply chain and thus with the economic sustainability of the product system. Following this line of thought, the SPOTTER approach offers quantitative evaluations for the economic dimension of the LCSA framework by assessing economic impacts in two midpoint impact categories, cost variability and limited availability.

3.2 Impact assessment within the SPOTTER approach

The impact assessment within the SPOTTER approach is to be integrated into the LCSA framework and should follow the basic concept of impact assessment applied in LCA, i.e. multiplication of material flows with CFs that define the impact. This section therefore defines first the generic calculation procedures in line with this basic concept in section 3.2.1 and 3.2.2 and it explains then the procedures for the specific calculation of the CFs and for the identification of indicators used in these calculations in section 3.2.3 and 3.2.4. An overview of the different elements for this impact assessment is finally provided in section 3.2.5.

3.2.1 Generic calculation procedures of impact scores

The evaluation of overall supply disruption impacts and the identification of supply disruption hotspots are based on the calculation of impact scores for all inventory flows of the product system. Each impact score is calculated by the multiplication of the amount of the specific resource, material or product that is used for a unit process ($\mathrm{m}_{\mathrm{mat\_UP}}$) with the respective CF that defines one type of supply disruption impact ($\mathrm{CF}_{\mathrm{mat\_UP}}$).

Equation (8) describes the first step that provides the scores for all bottlenecks of one impact category, which can then be used to identify the supply disruption hotspots.

$$\boldsymbol{Bottleneck\ score_{mat\_UP} = m_{mat\_UP} * CF_{mat\_UP}} \tag{8}$$

The overall supply disruption impacts of the product system ($impact\ score_{PS}$) is the sum of all bottleneck scores from the product system, as shown in Equation (9).

$$\boldsymbol{Impact\ score_{PS}} = \sum_{\boldsymbol{mat\_UP}} \boldsymbol{Bottleneck\ score_{mat\_UP}} = \sum_{\boldsymbol{mat\_UP}} \boldsymbol{m_{mat\_UP} * CF_{mat\_UP}} \qquad (9)$$

3.2.2 Generic calculation procedures of characterization factors

All CFs that are used in Equation (8) and (9) are derived from different characterization models. These characterization models are based on concepts from classical risk theory. Following the explanations of Glöser et al. (2015) and Frenzel et al. (2017), these characterization models consider both the probability of occurrence and the consequences of supply disruptions. They are based on two consecutive, overlapping cause-effect chains to model the combined supply disruption effects of occurrence and consequence. Within the first type of cause-effect chain, the probability of changing external conditions over a certain period is considered in combination with the limited diversity of supply[9]. These two aspects are combined to evaluate the probability of decrease in supply or increase in demand. Within the second type of cause-effect chain, the probability of decrease in supply or increase in demand is considered in combination with the vulnerability to such a decrease/increase. The result is then used to model the potential supply disruption impact for the analyzed flow. The considered indicators in these two cause-effect chains are presented in Figure 11.

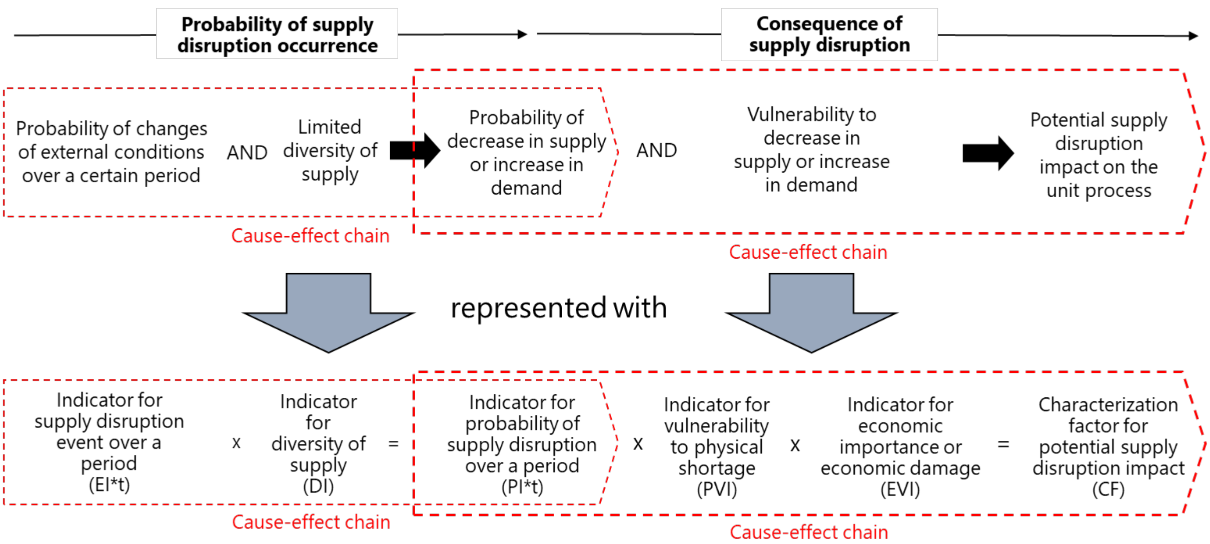

Figure 11: Description of cause-effect chains and indicators
used to calculate the characterization factors for the evaluation of potential supply disruption impacts

[9] Following Brown (2018), *diversity of supply* is defined as the degree to which the overall supply is constituted of just a few major suppliers.

The first cause-effect chain is described by the indicator for the supply disruption event over a period t (EI*t) and the indicator for the diversity of supply (DI) that are combined in the indicator for the probability of supply disruption over a period t (PI*t). The second cause-effect chain is described by the indicator for the probability of supply disruption over a period t (PI*t), the indicator for vulnerability to physical shortage (PVI), and the indicator for economic importance or economic damage (EVI). These four basic indicators are thus multiplied to calculate the CFs for the impact categories as shown in Equation (10).

$$\boldsymbol{CF} = (\boldsymbol{PI} * \boldsymbol{t}) * (\boldsymbol{PVI}) * (\boldsymbol{EVI}) = (\boldsymbol{EI} * \boldsymbol{t}) * (\boldsymbol{DI}) * (\boldsymbol{PVI}) * (\boldsymbol{EVI}) \tag{10}$$

3.2.3 Specific calculation procedures of characterization factors

Following the presentation of generic calculation procedures of CFs in section 3.2.2, this section aims to describe the procedures for specific calculations of these CFs. Different calculation principles are followed for these procedures. These principles are required to consider the different: time horizons (i.e. short- or medium-term), spatial scopes (i.e. country-specific or global), inventory flows (i.e. resource or material/ product) and impact categories (i.e. cost variability or limited availability). Calculations following the same principles are grouped together to a *group of supply disruption impact*. An overview of the resulting eight groups is given in Table 4 and their specific calculation principles are presented in the following paragraphs of this section.

Table 4: Overview of the supply disruption impact groups of the SPOTTER approach

<table>
<tr><th rowspan="2">Impact categories and types of inventory flows
Time horizon</th><th>Cost variability</th><th colspan="2">Limited availability</th></tr>
<tr><th>Material/product</th><th>Resource</th><th>Material/product</th></tr>
<tr><td rowspan="2">Short-term (ST)</td><td>Country-specific
(Group 1)</td><td rowspan="2">Country-specific
(Group 3)</td><td>Country-specific
(Group 4)</td></tr>
<tr><td>Global
(Group 2)</td><td>Global
(Group 5)</td></tr>
<tr><td>Medium-term (MT)</td><td>Global
(Group 6)</td><td>Country-specific
(Group 7)</td><td>Global
(Group 8)</td></tr>
</table>

It is distinguished between the eight groups of supply disruption impacts described in Table 4 due to four reasons:

First, calculations referring to short-term (ST) and medium-term (MT) assessments constitute different groups, as different inventory flows (m) and CFs are considered for the ST assessment and for the MT assessment. The m(ST) and CF(ST) values are determined from data that is specific to the current situation and can be acquired, for example, from trade databases or geological surveys. Conversely, m(MT) and CF(MT) values are defined by different future scenarios, which are created using, for example, data from technology roadmaps (see section 3.3 for an example of data sources that can be used for ST or MT assessments).

Second, the impact scores for the category of limited availability are assessed for both resource and material/product flows, while the impact scores for the category of cost variability are only assessed for material/product flows. Fluctuating extraction costs are not considered separately in the SPOTTER approach because, following Henckens et al. (2014), it is assumed that fluctuations in these costs change the resource availability.

Third, ST assessments of material/product flows consider country-specific and global events, while MT assessments of material/product flows mainly consider global events. An exception is the event related to resource depletion, which, as explained in the next paragraph, is only considered on a country level. The analysis of mainly global events in MT assessments is because these assessments are particularly concerned about the global supply situation or because data acquisition on a country-level is challenging for MT events that are specific to countries.

Fourth, only country-specific events are considered for the assessment of resources since the inventory flows are analyzed in relation to specific stocks that are defined at the country level.

The specific calculation for the CFs of these eight groups of supply disruption impacts are described below. The two examples introduced in Figure 10 are considered to explain the choices of the different indicators that are used for the calculations of the CFs. The first example describes a unit process in country k that extracts resource R from the resource stock in the same country to produce the mineral M. The second example describes a unit process in country i that produces raw material A, which is then used by the unit process in country c to manufacture product P. The following equations (11) to (18) describe the specific calculations for the eight groups in relation to the generic calculation shown in Equation (10).

Generic calculation

$$CF = (EI * t) * (DI) * (PVI) * (EVI)$$

Group 1: Country-specific ST cost variability of material/product flows

$$CF(ST)_{APic} = (EI_{Ai} * t) * \left(\frac{import_{Aic}}{production_{Ac} + import_{Ac}}\right) * \left(\frac{production_{A,GLO}}{(in\_use\ stock_{A,GLO})^2}\right) * \left(\frac{cost_{APic}}{cost_{A,SC}}\right) \tag{11}$$

Group 2: Global ST cost variability of material/product flows

$$CF(ST)_{APc} = (EI_A * t) * \left(\left(HHI_{Ai,GLO} * \frac{1}{n}\right) \Big/ \left(1 - \frac{1}{n}\right)\right) * \left(\frac{production_{A,GLO}}{(in\_use\ stock_{A,GLO})^2}\right) * \left(\frac{cost_{APc}}{cost_{A,SC}}\right) \tag{12}$$

Group 3: Country-specific ST limited availability of resource flows

$$CF(ST)_{RMk} = (EI_{Rk} * t) * (DI_{Rk}) * \left(\frac{production_{M,GLO}}{(in\_use\ stock_{M,GLO})^2}\right) * \left(\frac{cost_{Mk}}{cost_{M,SC}}\right) \tag{13}$$

Group 4: Country-specific ST limited availability of material/product flows

$$CF(ST)_{APic} = (EI_{Ai} * t) * \left(\frac{import_{Aic}}{production_{Ac} + import_{Ac}}\right) * \left(\frac{production_{A,GLO}}{(in\_use\ stock_{A,GLO})^2}\right) * \left(\frac{cost_{Pc}}{cost_{P,SC}}\right) \tag{14}$$

Group 5: Global ST limited availability of material/product flows

$$CF(ST)_{APc} = (EI_A * t) * \left(\left(HHI_{Ai,GLO} * \frac{1}{n}\right) \Big/ \left(1 - \frac{1}{n}\right)\right) * \left(\frac{production_{A,GLO}}{(in\_use\ stock_{A,GLO})^2}\right) * \left(\frac{cost_{Pc}}{cost_{P,SC}}\right) \tag{15}$$

Group 6: Global MT cost variability of material/product flows

$$CF(MT)_{APc} = (EI_A * t) * \left(\left(HHI_{Ai,GLO} * \frac{1}{n}\right) \Big/ \left(1 - \frac{1}{n}\right)\right) * \left(\frac{production_{A,GLO}}{(in\_use\ stock_{A,GLO})^2} * SPI_A\right) * \left(\frac{cost_{APc}}{cost_{A,SC}}\right) \tag{16}$$

Group 7: Country-specific MT limited availability of resource flows

$$CF(MT)_{RMk} = (EI_{Rk} * t) * (DI_{Rk}) * \left(\frac{production_{M,GLO}}{(in\_use\ stock_{M,GLO})^2}\right) * \left(\frac{cost_{Mk}}{cost_{M,SC}}\right) \tag{17}$$

Group 8: Global MT limited availability of material/product flows

$$CF(MT)_{APc} = (EI_A * t) * \left(\left(HHI_{Ai,GLO} * \frac{1}{n}\right) \Big/ \left(1 - \frac{1}{n}\right)\right) * \left(\frac{production_{A,GLO}}{(in\_use\ stock_{A,GLO})^2} * SPI_A\right) * \left(\frac{cost_{Pc}}{cost_{P,SC}}\right) \tag{18}$$

Where:

The indicators for supply disruption events over a period (EIs*t) are:

- $EI_{Ai} * t$: indicator for supply disruption event affecting the supply of raw material A from country i over period t
- $EI_A * t$: indicator for supply disruption event affecting the global supply of raw material A over period t
- $EI_{Rk} * t$: indicator for supply disruption event affecting the extraction of resource R from country k over period t

The indicators for diversity of supply (DIs) are:

- $\frac{import_{Aic}}{production_{Ac}+import_{Ac}}$: share of import from country i in the market of raw material A for country c complemented with domestic production in country c
- $\left(\left(HHI_{Ai,GLO} * \frac{1}{n}\right) / \left(1 - \frac{1}{n}\right)\right)$: Herfindahl-Hirschman Index (HHI) for raw material A produced by a number n of countries i, calculated as the sum of the squares of the shares for each producing country (Herfindahl 1950; Hirschman 1945). HHI is calculated on a normalized basis following the description in Brown (2018).
- DI_{Rk}: the indicator for the diversity of supply of resource R is determined as 1, because the unit process in country k only extracts the resource from the stock in country k

The indicators for vulnerability to physical shortage (PVIs) are:

- $\frac{production_{A,GLO}}{(in\_use\ stock_{A,GLO})^2}$: ratio of global production of raw material A to the global in-use stock of raw material A to the square
- $\frac{production_{M,GLO}}{(in\_use\ stock_{M,GLO})^2}$: ratio of global production of mineral M to the global in-use stock of mineral M to the square
- SPI_A: indicator for the performance of a substitute for raw material A

The indicators for the economic importance/damage (EVIs) are:

- $\frac{cost_{APic}}{cost_{A,SC}}$: ratio of cost of raw material A from country i to produce product P in country c to the overall cost of material A in the analyzed supply chain
- $\frac{cost_{APc}}{cost_{A,SC}}$: ratio of cost of raw material A to produce product P in country c to the overall cost of material A in the analyzed supply chain
- $\frac{cost_{Pc}}{cost_{P,SC}}$: ratio of revenue of the product P produced in country c to the overall revenue of product P in the analyzed supply chain
- $\frac{cost_{Mk}}{cost_{M,SC}}$: ratio of revenue of the mineral M produced in country k to the overall revenue of mineral M in the analyzed supply chain

Indicators for supply disruption events over a period

The indicators for supply disruption events (EIs) describe the probability of occurrence for different supply disruption events. The definition of EIs depends on the spatial scope of the supply disruption event that is considered. When analyzing country-specific events, EI_{Rk} or EI_{Ai} are used, while, when analyzing global events, EI_A is used. The identification of specific EIs requires the use of a specific heuristic that is described in section 3.2.4. In all CF calculations, the event duration t is multiplied with the EI score. A specific period of event occurrence can be considered, if data is available (e.g. from empirical studies). If such data is not available, a period equal to the time horizon of the study is assumed (i.e. ST = 5 years, MT = 10 years).

Indicators for supplier diversity

The indicators for supplier diversity (DIs) provide an evaluation of the potential effects from market concentration (Gemechu et al. 2015b) or production concentration (Brown 2018), where higher concentrations refer to a higher probability of a supply disruption in both cases. The type of the concentration evaluation depends on the scope of the supply disruption event that is considered. When analyzing country-specific events, the country's market concentration is used because it represents the disruption probability for supply in different countries. Following Helbig et al. (2016c), the indicators are defined by import shares of potentially disrupted materials/products from specific countries complemented with domestic production (assumed to be risk-free). Conversely, when analyzing global events, the global concentration of material/product production is considered because, as explained by Brown (2018), a higher risk of global supply disruption exists when production is limited to few countries. To define production concentrations, the Herfindahl-Hirschman Index (HHI) is used as an indicator, since, as explained by Calkins (1983), it is a straightforward way to consider asymmetric market shares and production shares for every country. To avoid the dominance of the DI in the calculations, the HHI needs to provide results ranging from 0 to 1 and it is thus calculated on a normalized basis following the explanation by Brown (2018). An exception is the DI for resources, which is calculated neither by import shares nor by the normalized HHI, but is defined as “1”. This is because the relevant inventory flows always originate from the country-specific stocks and the resource extraction is thus considered to be 100% concentrated in the country where the extraction occurs.

Scaling of indicators for probability of supply disruption

To be able to compare impacts that are caused by different supply disruption events, values of the indicators for probability of supply disruption (PIs), i.e. EIs multiplied with DIs, are scaled from 0 to 1. The scaling procedure is adapted from the approach of Bach et al. (2017b) and follows Equation (19).

$$\boldsymbol{PI\ score} = \frac{\left(\boldsymbol{PI\ value_{original}} - \boldsymbol{PI\ value_{min}}\right)}{\left(\boldsymbol{PI\ value_{max}} - \boldsymbol{PI\ value_{min}}\right)} \tag{19}$$

where:

- $PI\ score$: score of the indicator for supply disruption probability used for the calculation of the characterization factor
- $PI\ value_{original}$: original value of the indicator for supply disruption probability
- $PI\ value_{min}$: lowest value of the indicator for probability of supply disruption caused by a specific event in the considered supply chain
- $PI\ value_{max}$: highest value of the indicator for probability of supply disruption caused by a specific event in the considered supply chain

Following the calculation presented in Equation (19), the value 1 represents the highest supply disruption probability and the value 0 the lowest probability within the evaluation of the supply chain. When different supply chains are analyzed (e.g. cobalt and aluminium supply chains), the same scale is considered across all applied PIs.

Indicators for vulnerability to supply disruption

In the SPOTTER approach, the indicators for vulnerability to supply disruption comprise (i) an indicator for vulnerability to physical shortage (PVI), (ii) an indicator for substitutability options (SPI) and (iii) an indicator for economic importance or the economic damage (EVI). According to Helbig et al. (2016a), all three indicators describe important characteristics of vulnerability assessments. The substitutability options are representations of measures to mitigate physical shortage of material in the medium-term and are thus considered as part of the PVI in Equations (16) and (18).

Indicators for vulnerability to physical shortage

The interpretation of the PVIs follow the principle that the product system is less vulnerable to physical shortage, when the required materials, components or products are recycled, remanufactured or reused from the in-use stock and do not need to do not need to be acquired from limited primary production. PVIs are defined as a ratio between global annual production and global stocks to the square following the approach developed for the Abiotic Depletion Potential (ADP) method (van Oers et al. 2002). As argued by Klinglmair et al. (2013), the denominator needs to be squared in this calculation to indicate that the impacts are higher for lower production amounts with smaller stocks compared to higher production amounts with larger stocks. Indeed, a ratio without a squared denominator could not distinguish the different levels of vulnerability between these two cases.

Indicators for substitutability options

Following the approach described by the European Commission (2017a), SPIs are used to represent the performance of a substitute for the considered material. Here, a scale from 0 to 1 is applied with 1 indicating poor substitution performance. Regarding the definition of substitutability indicators that are specifically defined for the SPOTTER approach, the following five characteristics are considered.

First, these indicators are only applied to MT assessments because the implementation of substitutes often requires a few years or decades. On that note, Ku et al. (2018) have pointed out that suitable substitution typically requires technology development, which may take up to 20 years. Here, the 5 years period considered for ST assessments might often not be enough time to adapt or develop technologies.

Second, only the direct substitution of raw materials is considered. According to Cimprich et al. (2018), substitution needs to be distinguished between direct, i.e. replacing one raw material with a different raw material with similar properties, and indirect, i.e. exchanging one product with another product with a different design. Direct substitution is for example the use of manganese instead of cobalt in lithium-ion batteries. Indirect substitution, however, is for example using electric vehicles instead of conventional vehicles. On that note, Cimprich and colleagues argue that only direct substitution serves to mitigate supply disruption impact of the product system, while indirect substitution creates a new product system that requires a separate inventory analysis (Cimprich et al. 2018).

Third, only proven substitutes that allow reducing the consequences of supply disruption are considered. This kind of substitutes has also been considered in the approach described by the European Commission (2017a) because sufficient knowledge about a possible implementation only exists for these alternatives. This knowledge can for example be gained from commercial information or published patents regarding the specific substitution option.

Fourth, only the substitutability of the most likely substitute is considered for practicability reasons. Graedel et al. (2012) evaluate, for the same reasons, only the *primary substitute*, i.e. the substitute that will most likely be used, in their assessment and thus neglect additional substitution options. Such an evaluation is more practical because it reduces the complexity of substitute identification and calculation of the SPIs. The identification of the primary substitute in the SPOTTER approach is based on the four-point binary scale procedure developed by Graedel et al. (2012) to limit the influence of expert judgment for substitute selection. This procedure evaluates the capability of raw materials as potential substitutes according to their past use, current use and future use as well as analyzes significant differences in characteristics relevant for the intended application. Each of the four criteria is assigned a number of 0 or 1, with 1 indicating poor substitutability. Adding the numbers, the substitution options are rated from 0 to 4. After translating these numbers to default scores, exemplary, good, adequate and poor substitutes are indicated with scores of 0.125, 0.375, 0.625 and 0.875, respectively.

Fifth, flags are assigned to raw materials with critical substitutability options. Here, one flag is assigned to the raw materials, for which the substitute is described as a critical raw material by a regionally relevant study (e.g. the study conducted by the European Commission (2023) could be consulted for the scope of European countries), and two flags are assigned to raw materials if no suitable substitute is found. While the consideration of such "flags" offers the opportunity to raise the attention of decision makers, it does not allow for a purely quantitative assessment.

Indicators for economic importance/damage

EVIs are calculated differently depending on the considered type of impact category. When assessing cost variability, the EVIs are defined following the approach developed by Lütkehaus et al. (2022), who assess economic material importance. Costs of production and delivery are then considered as an indication of consequences from price increases of economically important materials/products. These costs are calculated by multiplying the price of material/products (in e.g. $/kg) with their amount (in e.g. kg). Conversely, when assessing limited availability, the EVIs are defined following Helbig et al. (2016a), who explain that a total supply disruption, i.e. the unavailability of required materials, affects the economic value of the process output. The revenues that are exposed to this supply disruption are thus used as indications of such an economic damage. These revenues are calculated by multiplying the price with the amount of the produced material/product. Only the revenues from potentially disrupted trade flows are considered relevant in the SPOTTER approach, while the domestically generated part of revenues is assumed to be risk-free in case of country-specific events. To evaluate the indicators in relation to the overall product system performance, all EVIs are defined in relation to the total cost of production and delivery or total revenue related to the supply of analyzed material/product within the supply chain (in e.g. $).

In the context of assessing limited availability, Cimprich et al. (2017) argue that all inventory flows are equally important for the product system performance and they therefore use the indicator *1 divided by the inventory flow* to "cancel out" the effects from the size of the inventory flows. Conversely, the SPOTTER approach is based on the concept that disruptions of smaller inventory flows are less harmful to the resilience of product systems and can be more easily compensated than the disruptions of larger inventory flows. Furthermore, Cimprich et al. (2019) emphasize that "canceling out" the magnitude of the inventory flows conceals the concept of resource efficiency, where minimizing the input is understood as an impact mitigation measure. The choice of the SPOTTER approach is therefore made to allow the identification of options where reducing the mass contribution can be used to mitigate the disruption risks from different flows of materials or products.

Case-specific characterization factors

The scaling of the PI values and calculations of EVIs show that these indicators are context dependent and thus the CFs are case-specific. This means that individual CFs need to be calculated for each case study and for different supply chains. Such case-specific CFs can also be found in other approaches integrating criticality assessment into LCSA such as the ones described by Cimprich et al. (2017, 2018).

After the calculation of impact scores for all inventory flows through their multiplication with the respective CFs, impact scores of the same impact category can be aggregated into a single value. Following the ESP approach (Schneider et al. 2013), consistent scaling of impact scores is applied in this aggregation because all indicators are defined from 0 to 1 (as explained above). Such an aggregation facilitates the interpretation and communication of results since the results are presented with two impact categories. An equal range is thus assumed for the probability of occurrence of the considered supply disruption events with the scaling of the SPOTTER approach. These specific events and their related indicators are carefully selected in section 3.2.4.

3.2.4 Procedure to identify indicators for supply disruption events

While specific DIs, PVIs and EVIs that are used for the specific calculations of the CFs have been defined in section 3.2.3, the specific EIs that are also required for these calculations still need to be defined. The heuristic diagram of Figure 12 has been developed in order to identify these EIs.

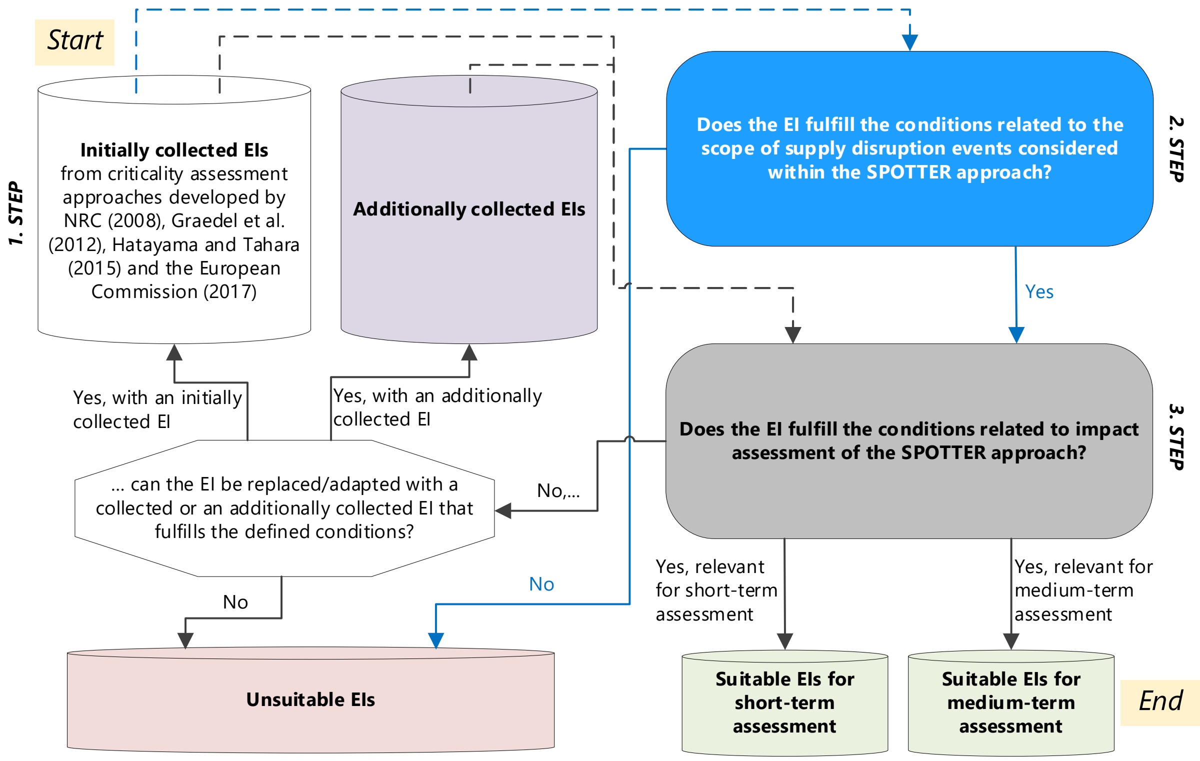

Figure 12: Heuristic diagram to identify indicators for supply disruption events (EIs) that are suitable for establishing calculations of characterization factors considered in the SPOTTER approach

In the first step of the heuristics described in Figure 12, an initial collection of EIs has been compiled (white box in Figure 12). The respective EIs have been collected from the following four approaches:

- the National Research Council (NRC) approach (NRC 2008),
- the Yale University (Yale) approach (Graedel et al. 2012),
- the New Energy and Industrial Technology Development Organization (NEDO) approach (Hatayama and Tahara 2015) and,
- the European Commission (EC) approach (European Commission 2017a).

As explained in section 2.2.1, these four approaches are perceived as pioneering work in the field of criticality assessment. They are thus implemented on a large scale and serve as a base for many other approaches. A description of the scope and the included EIs is provided for each of the approaches in Appendix A.1.

In the second and third step of the heuristics, the EIs included in the initial collection undergo successively two indicator evaluation procedures (blue and gray squares in Figure 12). These procedures are based on ten conditions, which are described in Table 5 and further explained and justified in Appendix A.2.

During the first evaluation procedure (blue square in Figure 12), the EIs are compared against the conditions (1) to (3) described in Table 5. EIs that fulfill these conditions are suitable for the analysis of the supply disruption events that the SPOTTER approach considers. Besides these suitable EIs, the analyzed events are also identified through this evaluation (see section 3.2.5 for an overview of these events). EIs that do not fulfill these conditions are unsuitable for such an analysis and they are not considered in the SPOTTER approach. The suitable EIs undergo the second indicator evaluation procedure (gray square in Figure 12), where they are compared against the conditions (4) to (10) described in Table 5. By fulfilling these conditions, the EIs are suitable to comply with the requirements for an impact assessment within the SPOTTER approach. When the EIs do not fulfill one of the seven conditions, a possible replacement/adjustment of the EIs is investigated. Options for replacement/adjustment are found by the use or adaption of other initially collected EIs (white box in Figure 12) or additionally collected EIs (purple box in Figure 12). Details regarding the evaluation of each collected EI according to the defined conditions are provided in the Appendix A.3. As shown in Figure 12, the EIs that are then identified as suitable for the establishment of the SPOTTER approach are collected in the two green boxes. These two boxes include two sets of EIs, one for the ST assessment and another one for the MT assessment. An overview of the selected EIs is given in section 3.2.5 and detailed descriptions of these EIs are provided in the Appendix A.5.

Table 5: Conditions to be fulfilled by indicators for supply disruption events (EIs) so that they are suitable for establishing calculations of characterization factors considered in the SPOTTER approach

No.	***Requirement***	***Condition***
(1)	Reducing computational and data acquisition efforts as well as ensuring the feasibility of the assessments	Does the EI represent supply disruption events that are analyzed by at least 10% of the criticality assessment approaches that are reviewed by Schrijvers et al. (2020b) (see indicators for supply disruption probability listed in Figure 8)?
(2)	Avoiding double-counting of the contribution of a specific risk aspect	Does the EI refer to an aspect of supply disruption risk that has not already been described with another indicator included in the calculations?
(3)	Addressing the considered time horizons	Does the EI represent an event relevant for a ST or MT assessment (see distribution of indicators into time horizons described in Figure 8)?
(4)	Ease the identification of the origin of supply disruptions	Does the EI refer to only one specific causation of the supply disruption event?
(5)	Avoiding burden-shifting between impacts of different materials/products	Is the analysis of the supply disruption event independent of the type of material/product? If not, does the EI, in comparison to other indicators for the same event, allow for the broadest coverage of materials/products?
(6)	Avoiding burden-shifting between impacts of different resource types	Does the EI allow for the assessment of biotic and abiotic resources?
(7)	Avoiding burden-shifting between impacts caused by events occurring in different countries	In case of country-specific events, does the EI provide the broadest coverage of countries in comparison to other indicators for the same event?
(8)	Avoiding lack of data and allowing the provision of reproducible results	Can publicly available data be used to quantify the EI?
(9)	Allowing for MT assessments based on future scenarios	Is it possible to adjust EI values with different future scenarios for MT assessments?
(10)	Allowing for a consistent interpretation of results	Do higher values of the EI describe higher impact scores?

3.2.5 Overview of the resulting impact assessment elements

The resulting impact assessment within the SPOTTER approach comprises three different elements: (i) the specific events that cause the supply disruption, (ii) the specific CFs that define the supply disruption impacts by the use of different indicators and (iii) the specific impact categories that represent the supply disruption impact. Figure 13 provides an overview of these three elements and shows how the CFs are calculated by different combinations of the specific EIs, DIs, PVIs and EVIs that have been identified in the sections 3.2.3 and 3.2.4.

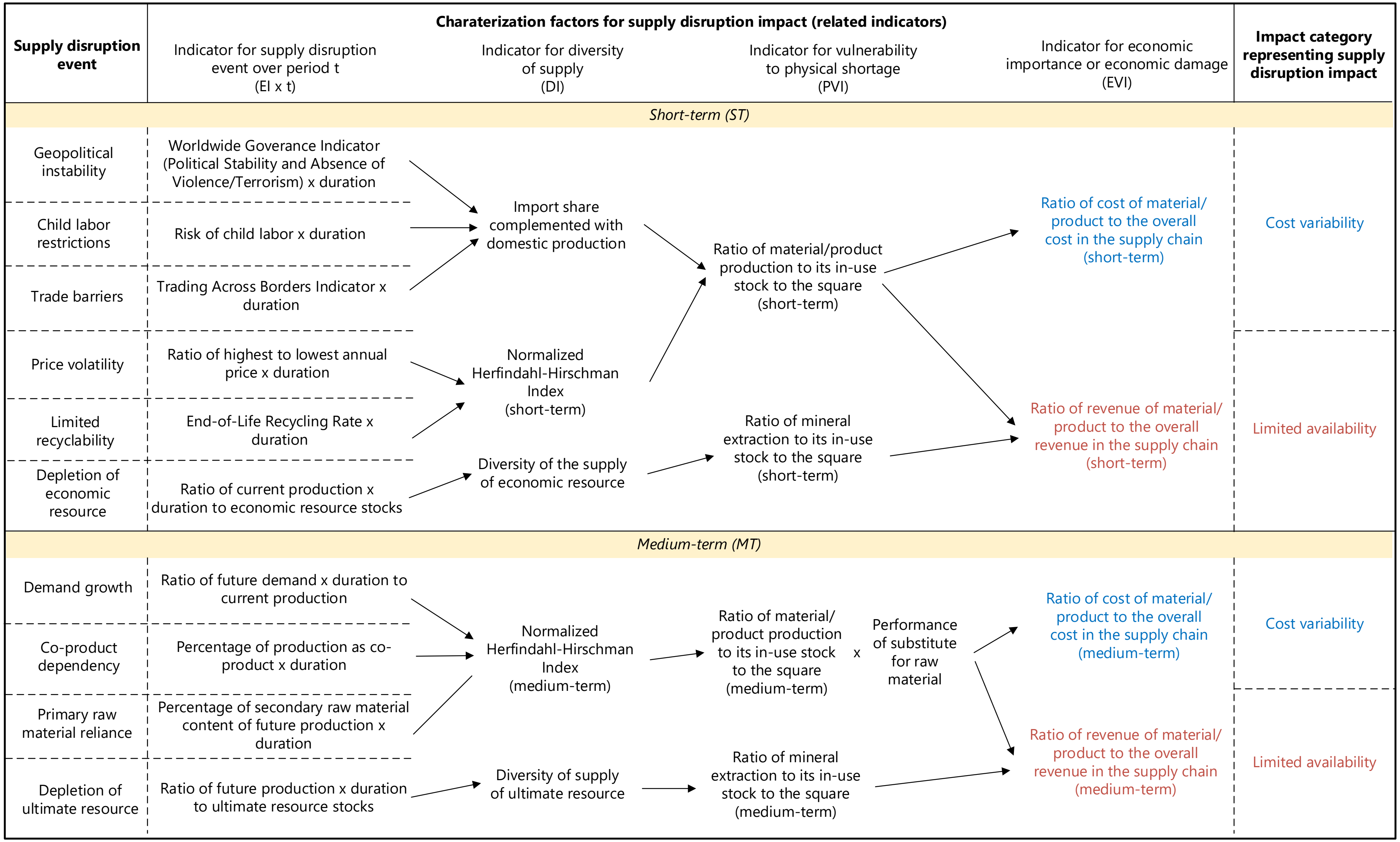

Figure 13: Synopsis of events, characterization factors and impact categories used for the assessment of supply disruption impacts with the SPOTTER approach

These combinations of indicators used for the ST and MT assessments are visualized with arrows as well as blue and red colors in Figure 13. As it can be seen from Figure 13, the use of the consequently defined CFs depends on the analysis of the considered supply disruption events and impact categories. While the two impact categories analyzed in the SPOTTER approach have been explained in section 3.1, further details regarding the analyzed supply disruption events are provided in the following paragraphs.

The ten different events analyzed in the SPOTTER approach have been identified during the first indicator evaluation procedure described with a blue square in Figure 12, because EIs that are selected with this procedure define the scope of analyzed events. Table 6 lists these events and presents the time horizons, affected inventory flows and geographical scope related to each event. Detailed descriptions of the events are provided in the Appendix A.4.

Table 6: Supply disruption events considered in the SPOTTER approach

Time horizon	Affected inventory flows (X)					Event	Geographical scope
	Re	Mi	RM	IP	FP		
Short-term (ST)		X	X	X	X	**Geopolitical instability**	Country-specific
		X	X	X	X	**Child labor restrictions**	
		X	X	X	X	**Trade barriers**	
	X					**Depletion of economic resource**	
			X			**Limited recyclability**	Global
		X	X	X	X	**Price volatility**	
Medium-term (MT)		X	X	X	X	**Demand growth**	Global
		X	X	X	X	**Co-product dependency**	
				X		**Primary raw material reliance**	
	X					**Depletion of ultimate resource**	Country-specific

Re: Resource, Mi: Minerals, RM: Raw materials, IP: Intermediate products, FP: Final products

As shown in Table 6, ten supply disruption events are considered in the SPOTTER approach. Six of them are relevant for ST assessments and four of them are relevant for MT assessments. The relevance of events for a certain time horizon has been analyzed mainly from the explanations provided by Glöser et al. (2015) and Ku et al. (2018). Social, trade and recycling regulations or the geopolitical instabilities are considered in ST assessments because these events may change quickly and have immediate effects in the near future (for example in case of elections of new governments or different parties). Similarly, price volatility is relevant in the ST assessment because frequent fluctuations in supply and demand may affect the market prices daily. Conversely, the example of demand growth is considered in MT assessments because growing demand is likely to have no or small effects in the ST but should lead to progressing resource depletion or potential production capacity bottlenecks in the MT horizon (Jasiński et al. 2018). In case of co-product dependency and primary raw material reliance, similar observations to the one of demand growth have been reported by Glöser et al. (2015) and Ku et al. (2018). The relevant time horizon for resource depletion is dependent on the resource state. As explained by Schneider et al. (2011), economic resources (i.e. those that are economically extractable today) are relevant for ST assessments, while ultimate resources (i.e. those that are fulfilling chemical and physical criteria for extraction but are not economically extractable today) are relevant for MT assessments.

Table 6 also shows that the considered supply disruption events may affect all inventory flows along the supply chain when they are collectively considered. The majority of events leads to potential disruptions of mineral, raw material, intermediate product or final product flows. Other events such as resource depletion, limited recyclability or raw material reliance may only affect one specific type of inventory flow.

Finally, Table 6 shows that five country-specific and five global supply disruption events are considered with the SPOTTER approach. Following Bach et al. (2017b), unstable governance situations, national policy regulations and bilateral trade barriers are examples of country-specific events. Technologies demand growth, volatile market prices and co-product dependency are considered as global events. In the SPOTTER approach, resource depletion is analyzed on the country level because impacts are assessed for mineral flows between a country-specific resource stock and a unit process (see Figure 10). Raw material reliance is analyzed on the global level because country-specific data about raw material contents of products is difficult to find (Bach et al. 2017b).

3.3 Procedure for the Use of the SPOTTER Approach

The implementation of the SPOTTER approach is expected to be challenging due to the limited data availability for comprehensive assessments along the supply chain. This section therefore presents a procedure to simplify the evaluation of potential supply disruption impacts with the SPOTTER approach. This procedure is based on the five steps summarized in Figure 14.

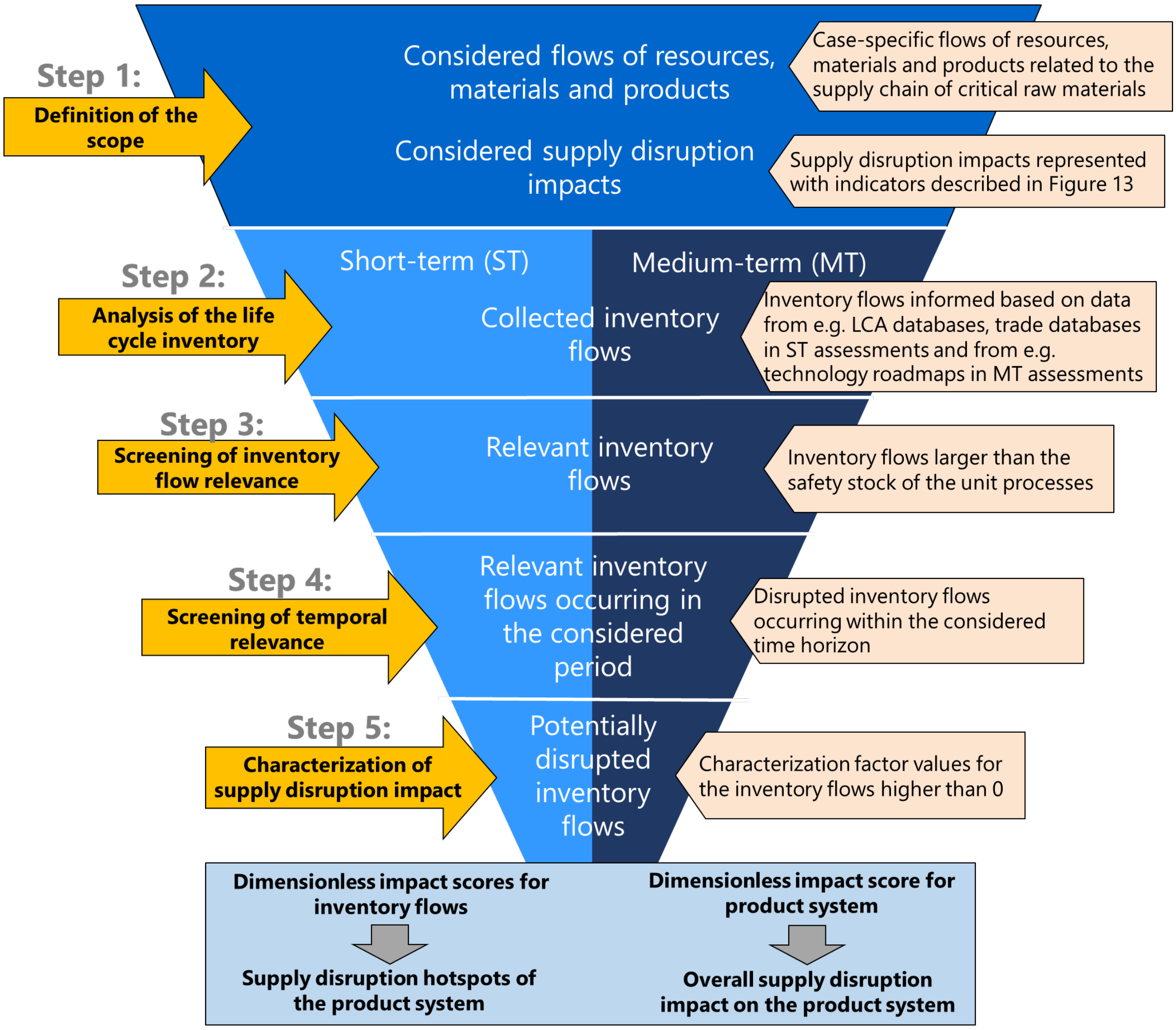

Figure 14: Five-step procedure for the implementation of the SPOTTER approach

The first step requires the definition of the scope of the analysis with statements on the considered: resource, material and product flows as well as supply disruption impacts. All known inventory flows of the product system are considered in the LCSA framework but the SPOTTER approach limits its analysis to raw materials included in a list of critical raw materials relevant for the considered country/region. For example, the list of critical raw materials published by the European Commission (2023) could be considered in the case of an assessment of European countries. The case-specific flows that occur along the supply chain of these raw materials are then analyzed. These choices reduce the efforts for data acquisition. Ideally, the chosen supply disruption impacts would be represented with best-suited indicators. However, since these indicators might not always be available, choices for indicator use are made following the indicator identifications described in section 3.2.3 and 3.2.4.

The second step requires the modeling of the assessed product systems and the calculation of the inventory flows that are considered with the SPOTTER approach. In a perfect world, it would be possible to inform about the precise time and geography associated with all inventory flows within the considered supply chain. In practice, certain inventory flows or temporal and geographical description will not be known. These issues of data availability are particularly expected for the MT assessments. Hence, within a first implementation, at least two different models of the product system are considered: one for the ST assessment incorporating inventory flows that are representative of the next 5 years and a second one for the MT assessment, which considers the inventory flows that will occur between the next 5 to 15 years. Data from databases including for example ecoinvent (Wernet et al. 2016), EXIOBASE (Wood et al. 2015) and/or trade databases (e.g. BACI (Gaulier and Zignago 2010)) can be used for ST assessment since these databases are representative of the current flows in the product system. Data provided in literature such as the reports of IEA (2020a) and IEA (2021) providing technology forecasts and roadmaps should be chosen for MT assessments because expected future trends are considered and explained in such documents to provide a transparent prospective model of the product system.

The third step involves a second screening of inventory flows by their relevance in the assessment of the supply disruption impacts. With regard to this further screening, the SPOTTER approach assumes that chosen unit processes have basic safety stocks to ensure their viability when minor disruptions occur (Gonçalves et al. 2020). Inventory flows that are lower than this basic safety stock can be removed from the assessment of supply disruption impacts to reduce the data needs to a limited number of inventory flows. Gonçalves et al. (2020) show that safety stocks are typically determined by various parameters differing for most processes. Because comprehensive data on safety stocks is currently missing, the SPOTTER approach assumes that these stocks are equivalent to 1% of the market (i.e. import and domestic production) from which the material/product is purchased. Inventory flows that are lower than this 1% boundary are therefore not considered in the analysis.

The fourth step filters the considered inventory flows according to their temporal relevance. As a consequence of the simplified supply chain representation in the second step, certain inventory flows will occur outside of the considered time horizon and will therefore not contribute to the assessed impacts. For example, an electric vehicle may consume three batteries over its lifetime and the supply of these batteries is analyzed in the ST assessment. In reality, only one of these batteries may be supplied within the considered period because the second battery has already been supplied and the third battery will be supplied after the ST period. In this case, only one third of the modeled inventory flow would be relevant to be analyzed for the ST assessment. To tackle this issue, the lifetimes of the included materials/products are considered to define the temporal relevance of related inventory flows.

The fifth step is about the characterization of supply disruption impacts. In the SPOTTER approach a potential supply disruption impact is deemed noteworthy when the CFs values for the inventory flows are higher than 0. The number of CFs that should be calculated therefore depends on the geographical scope of the supply disruption events and the affected inventory flows. Considering the 193 countries recognized by the United Nations (2020), the maximum numbers of CFs is determined as follows:

- Country-specific event affecting mineral, raw material or intermediate product flows: $(193 * 193) - 193 = 37'056$ (i.e. the supply disruption events affect inventory flows between 193 countries but not the inventory flows within the same country)
- Country-specific event affecting final product flow: 193
- Country-specific event affecting resource flow: 193
- Global event affecting mineral, raw material or intermediate product flow: 193
- Global event affecting final product flow: 1

Furthermore, a new set of CFs needs to be calculated when another supply disruption event or impact category (i.e. cost variability or limited availability) is considered. The previous calculations provide an evaluation of the maximum number of CFs that need to be defined in a case study, but this number can be lower when the supply chain does not depend on connections between all countries.

The five-step procedure of Figure 14 thus limits the calculation of the dimensionless impact scores to prioritized inventory flows. The overall impact assessments and hotspot analysis for supply disruptions can then be carried out for these inventory flows. The results are interpreted in two ways: (i) a comparison of the overall impacts between different product systems, which allows for the identification of the product system with relatively lower risks of supply disruptions and (ii) an analysis of the hotspots, which allows for the identification of key supply risks that should be treated with the highest priority. The SPOTTER approach recommends treating the additionally defined supply risks according to the principle that a higher impact score implies a greater need for risk mitigation.

The SPOTTER approach and other approaches assessing criticality within LCSA are used to identify risk mitigations measures such as resilient supply chain network design or alternative technology use (Fattahi et al. 2017; Ku et al. 2018). In contrast to these other approaches, the SPOTTER approach provides fine-tuned insights into potential supply disruption impacts by evaluating the most important supply risks along entire, global supply chains and over the short- and medium-term period. These insights can help to better anticipate supply risks and identify more effective risk mitigation measures, which would not be based mainly on short-term impacts of raw materials, as currently done, but also on short- and medium-term impacts along the complete supply chain. In that sense, the SPOTTER approach will facilitate the establishment of more resilient and sustainable supply chains and the implementation of technologies associated with lower supply risks.

3.4 Conclusion on the SPOTTER Approach

The SPOTTER approach proposes a novel way to quantitatively evaluate potential supply disruption impacts along the supply chain in the short- and medium-term within the Life Cycle Sustainability Assessment (LCSA) framework. The use of this approach allows for assessing the overall supply disruption impacts and for carrying out a hotspot analysis. While the overall impacts are assessed based on the total of impacts along the supply chain, the hotspots are identified by key supply bottlenecks representing the inventory flows associated with the highest impacts.

The potential supply disruption impacts are assessed individually for all inventory flows that are modeled within the chosen scope. This scope is defined by the chosen: inventory flows between the country-specific unit processes, short- or medium-term time horizons, impact categories *cost variability* and *limited availability* as well as supply disruption events *geopolitical instability*, *child labor restrictions*, *trade barriers*, *price volatility*, *limited recyclability*, *depletion of economic resource*, *demand growth*, *co-product dependency*, *primary raw material reliance* and *depletion of ultimate resource*.

All impact scores are calculated by multiplying the amounts of the inventory flows with their respective characterization factors (CFs). The SPOTTER approach provides a way to calculate such CFs specifying the criticality for the system under study. Because criticality is context-dependent (see explanation in section 2.2.1), these CFs are case-specific. To define the CFs indicators of supply disruption probability and vulnerability are used, which are suitable to assess cost variability and limited availability caused by supply disruption events frequently considered in criticality assessment (see the ten events listed above). These indicators have been collected from existing criticality studies and adapted for their use in the SPOTTER approach. To identify suitable indicators representing the specific events, the suitability of such indicators for an assessment with the SPOTTER approach has been evaluated considering certain heuristics. The thereby considered conditions refer to the suitability (i) to represent specific event causations, (ii) to allow for an assessment along the different stages of the supply chains on country-level in the short- and medium-term, (iii) to quantify indicators based on publicly available data and (iv) to provide a consistent interpretation of results. Furthermore, the SPOTTER approach provides a strategy to aggregate the impacts caused by the individual events within the two considered impact categories. Following this strategy, the indicators for supply disruption probability are consistently scaled considering the minimum and maximum of the calculated indicator values.

While the implementation of the SPOTTER approach is expected to be challenging because of limited data availability, a procedure to simplify its use has been proposed in the end of the chapter. Guidelines are thus provided for the definition of the scope, the analysis of the life cycle inventory, the screening of the inventory relevance, the screening of the temporal relevance as well as the calculation of CFs defining the supply disruption impacts.

In comparison with existing approaches, the SPOTTER approach enables a more comprehensive evaluation of supply disruption impacts along the supply chain within LCSA. However, limitations regarding practicability and representativeness of the SPOTTER approach have to be considered.

Concerning limitations linked to practicability, first, a comprehensive quantification of the assessed supply disruption impacts requires high data gathering efforts. Those efforts could be reduced if databases are developed with more details on the flows along supply chains for specific products.

Secondly, new CFs have to be calculated for each case study, as some of the indicators are case-specific. To reduce these efforts, a list of context independent values could be generated for some indicators. Finally, the results for the supply disruption impacts are provided in form of relative impact scores with dimensionless units that can be challenging for interpretation by decision makers. A way to provide results that are less differentiated and complex could be linked to the development of an appropriate endpoint indicator, where future research could build on possible endpoints suggested by Dewulf et al. (2015b) or the endpoint indicator for the GeoPolRisk approach developed by Santillan et al. (2020).

Concerning limitations linked to representativeness, first, the level of coverage of the considered supply disruption events might need to be improved. When events are covered that are frequently analyzed in the various criticality assessment approaches, it does not automatically mean that all the relevant events responsible for actual supply disruptions are addressed. Further research on the identification of appropriate indicators for supply disruption event is therefore useful. Secondly, as highlighted by Bach et al. (2016), the probabilities of occurrence for considered supply disruption events might not be well represented by a linear scaling from 0 to 1 as it is done in the SPOTTER approach. Then such a scaling implies a similar probability of all analyzed events. Hence, the usefulness of this scaling scheme need to be validated and, if necessary, adapted. Third, more representative and trustworthy sources of data on material/product flows that are used for the models of supply chains would be beneficial to the assessments. This is of particular interest for the models that provide prospective scenarios for the medium-term assessments.

As a next step, case studies will be carried out, in which the SPOTTER approach will be applied to three relevant sectors of the Swiss economy (i.e. mobility, energy and ICT sectors), one of the goals being to compare the results with those from other approaches. Based on these case studies, we will be able to derive more specific implications from the application of this new approach.

"A customer can have a car painted any color that he wants as long as it is black"

~ Henry Ford

4. Short-term assessment of electric vehicles used in Switzerland

Switzerland and 193 other countries have declared to become carbon neutral by 2050 by signing the Paris Agreement (UNFCCC 2015). The mobility sector, which plays a key role in Switzerland, is responsible for around 32% of the country's total carbon dioxide emissions (see Figure 3), making it one of the main contributors to these emissions (BAFU 2022; Ritchie et al. 2020). One possibility to decarbonize this sector is a shift from internal combustion engine vehicles towards electric vehicles (EVs), such as battery electric vehicles (BEVs) or plug-in hybrid electric vehicles (PHEVs), because these vehicles promise the potential for reduced carbon emissions in the mobility sector (Hirschberg et al. 2016; Lattanzio 2020; Sacchi et al. 2022). Policy support has already led to an exponential growth of EV sales over the last decade and this trend is expected to continue within the coming years (IEA 2020a).

However, events leading to disruptions of material and product flows along the supply chain of EVs may hinder their implementation and upscaling. Recently, the COVID-19 pandemic has caused shut-downs of EV battery production in China and global shortages of microprocessor chips in vehicles (Dyatkin and Meng 2020; Nicholas et al. 2021). Risks of further disruptions along EV supply chains are often estimated as high due to the complexity and fragility of the EV supply chain system (Wu et al. 2019) and the dependency of EV manufacturing on so-called "critical raw materials" such as cobalt, lithium or natural graphite (European Commission 2023; IEA 2020b). More resilient supply chains and better risk management should be established for electromobility to reduce the supply risks in the mobility sector.

Mechanisms leading to resilience in supply chains of neodymium magnets have been identified by Sprecher et al. (2015, 2017b) using a case study from the 2010 Rare Earth Crisis. These mechanisms include for example the increase in supply diversity, the improvement of material properties and substitution. In another study, Sprecher et al. (2017a) identify stockpiling as a suitable response option to significant short-term supply disruptions caused by unexpected events for metals produced as co-products.

To identify measures suitable for mitigating supply risks, potentially disrupted flows along the supply chains first need to be anticipated. Here, criticality assessment is useful as it allows for assessing the relative importance of supply disruptions for materials/products. Several criticality studies have already been performed with regard to the electromobility sector. For example, Helbig et al. (2018) have used a criticality assessment approach developed by Tuma et al. (2014) to assess the supply disruption impacts for raw materials used for different traction batteries.

Other studies have assessed supply disruption impacts by applying criticality assessment approaches integrated into the LCSA framework because such approaches offer, amongst other benefits, the possibility to avoid burden-shifting between supply disruption impacts and environmental impacts (see describption of benefits in section 1.3). For example, Gemechu et al. (2015a), Cimprich et al. (2017, 2018), Santillan et al. (2020) and Lütkehaus et al. (2022) have used and extended the GeoPolRisk approach developed by Gemechu et al. (2015b) to evaluate the impacts of raw materials utilized in EVs or traction batteries. Henßler et al. (2016) in turn have applied the ESSENZ approach developed by Bach et al. (2016) to assess the impacts of metals and fuels used in plug-in hybrid electric vehicles.

While various approaches assessing criticality within LCSA have been developed (see a list of approaches in Cimprich et al. (2019) and section 2.3), these approaches mainly focus on raw material supply as explained in section 2.5. There is thus a high risk of neglecting supply risks to be mitigated in terms of creating resilient supply chains. To tackle this issue, we have developed the SPOTTER approach that is assessing supply disruption impacts along the full supply chain within the LCSA framework.

This chapter aims at demonstrating the use of SPOTTER in a first case study, where impacts of supply disruptions are identified along the cobalt (Co) and aluminium (Al) supply chains of plug-in hybrid and battery electric passenger cars[10] used in Switzerland. EVs have been chosen as the case study object because of their growing importance as a more environmentally friendly mobility solution and the estimation of high disruption probabilities along their supply chains. Specifically, Co and Al supply chains are considered because Co and bauxite, the primary source of Al, are included in the list of critical raw materials for the European Union published by the European Commission (2020b) in 2020 and because both metals fulfill important functions for EV performance. Co is a crucial element in the cathode of the lithium-ion battery (LIB), which is currently the most widely employed battery type in EVs (Nature Editorial 2021). Al plays a significant role as a lightweight material in the structural part of the EV (Demirkesen and Uçar 2020), is an important wiring material (Yu 2016) and is used in cathode current collectors of LIB cells (Wang et al. 2019). Furthermore, considering Co and Al supply chains allows for testing SPOTTER by examples of two different types of materials, i.e. an abundant material (i.e. Al) and a scarce material (i.e. Co).

With the case study presented in Chapter 4 of this thesis, the following main research question is addressed:

> ***RQ2*: What are short-term impacts of potential supply disruptions along the supply chain of electric vehicles used in Switzerland?**

[10] To simplify, plug-in hybrid and battery electric passenger cars are collectively termed electric vehicles (EVs) in the continuation of this chapter.

To answer the main research question, the following two sub-research questions are addressed:

- *Q1*: How can material/product flows be defined and relevant impact scores be calculated along the supply chain?
- *Q2*: What are supply disruption hotspots related to the cobalt and aluminium supply chains of electric vehicles used in Switzerland?

This chapter is structured as follows: The methods and materials section (section 4.1) provides a first overview of the main elements of the SPOTTER approach and explains then the goal and scope definition, the quantification of inventory flows, the assessment of related impacts and the interpretation of results in terms of the present case study. In section 4.2, the results of the case study are presented, discussed and compared with results of criticality studies performed within and outside of LCSA as well as suggestions are made to mitigate the indicated supply risks. Section 4.3 finishes by drawing some conclusion and highlighting limitations and future research needs.

4.1 Methods and materials

4.1.1 Overview of main elements of the SPOTTER approach

SPOTTER is the first approach that is integrated into the LCSA framework and provides a quantitative assessment of supply disruption impacts along the full supply chain in the short- and medium-term. The goal of SPOTTER is to identify supply disruption hotspots, i.e. biggest supply bottlenecks, as well as overall supply disruption impacts, i.e. aggregated impacts along the supply chain. To achieve this objective, the inventory analysis, the impact assessment and the interpretation of results are performed in analogy to an LCSA. In the stage of inventory analysis, country-specific unit processes within the product system, i.e. processes along the supply chain that occur in different countries around the world, are defined and inventory flows that describe the inputs and outputs of these unit processes are collected. In the stage of impact assessment, impacts are evaluated individually for each of the collected inventory flows by multiplying inventory flow amounts with CFs that define specific supply disruption impacts. The sum of all calculated impact scores is then interpreted as the overall supply disruption impact and the highest impact scores are interpreted as supply disruption hotspots.

The elements considered for the impact assessment within SPOTTER comprise (i) supply disruption events, i.e. changes of conditions affecting the product system, (ii) case-specific CFs representing cause-effect chains between considered supply disruption events and impacts, as well as (iii) the specific impact categories comprising these impacts. Supply disruption events relevant for a short-term or a medium-term assessment have been described in section 3.2.5 and different indicators required for the calculation of the CFs have been selected in the sections 3.2.3 and 3.2.4, and pertinent impact categories have been defined in section 3.1. In addition, a practical procedure for the application of the SPOTTER approach, the so-called 'SPOTTER implementation procedure' has been proposed in section 3.3. In this chapter, this procedure, comprising five steps, is used for the performance of the case study (as shown in sections 4.1.2 to 4.1.5).

4.1.2 Goal and scope definition

An assessment of short-term impacts along the Co and Al supply chains of EVs used in Switzerland is performed following the 'SPOTTER implementation procedure' (see section 3.3). The two objectives are: (i) to identify supply disruption hotspots and (ii) to calculate scores for the overall supply disruption impact. The functional unit is the Swiss EV fleet in 2019.

Based on the first step of the 'SPOTTER implementation procedure', the focus is set on the causes (i.e. events) and impacts of supply disruptions that can be quantified with the indicators used in SPOTTER (see list of indicators in section 3.2.5). The country-specific events *geopolitical instability*, *child labor restrictions*, *trade barriers* and *depletion of economic resource* as well as the global events *price volatility* and *limited recyclability* are thus considered. Country-specific events refer to changes in conditions affecting the product system that occur in a specific country, while global events represent these changes related to the global market of a material/product. Considered impacts belong to two impact categories, "cost variability", which refers to the effects of price hikes, and "limited availability", which represents the effects of physical unavailability. A more in-depth description of the events and impact categories is provided in Appendix A.4 and section 3.1.

The model of the product system comprises all supply chain processes from the extraction of resources and the processing of minerals to the manufacturing of intermediate/final products (see upper part of Figure 15). The material/product-specific inputs and outputs of these processes are represented in the middle part of Figure 15. The choices related to this bill of materials are explained in Appendix B.1. The lower part of Figure 15 illustrates the supply disruption events that are analyzed at the different supply chain stages. Geopolitical instability, trade barriers and price volatility may lead to disruption of flows along the full supply chain. Conversely, child labor potentially occurs during artisanal mining of Co and bauxite, as reported by Banza Lubaba Nkulu et al. (2018) and Hentschel et al. (2003), but does probably not take place downstream of the supply chain for high-tech products such as EVs and traction batteries.

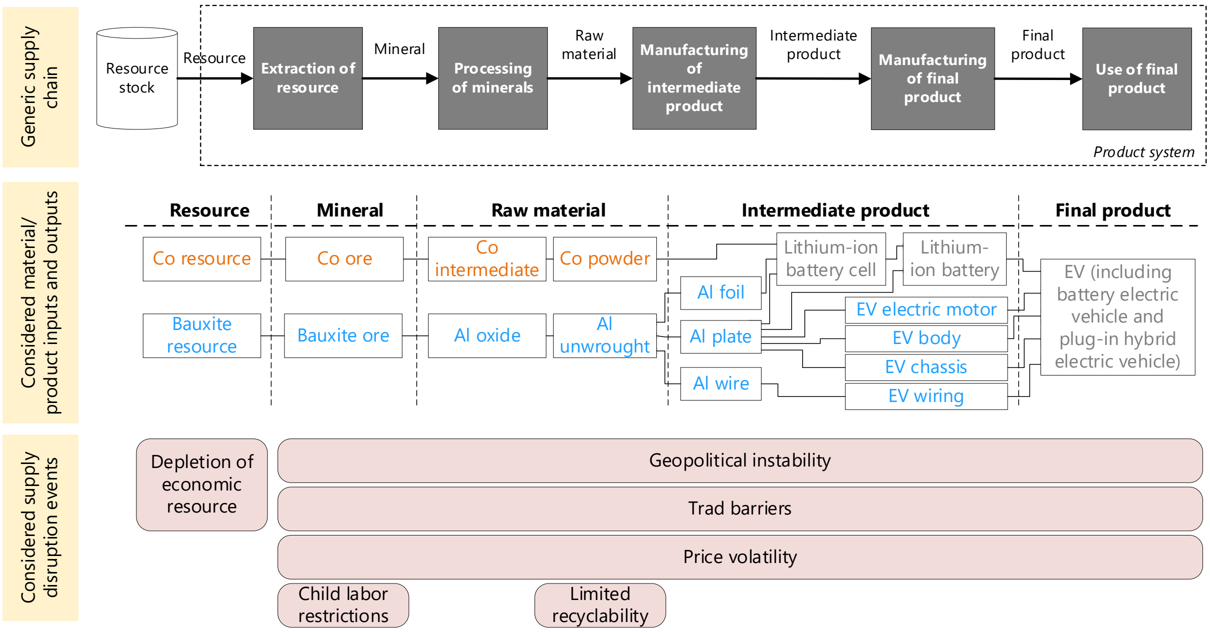

Figure 15: Description of inputs/outputs and supply disruption events
considered along the cobalt (Co) supply chain (in orange) and aluminium (Al) supply chain (in blue) or both supply chains (in grey) of electric vehicles (EVs)

The impact assessment with SPOTTER is performed as part of an LCSA framework and thus complements environmental impact assessment conducted with traditional process-based LCA studies. In the inventory analysis, inventory flows are quantified by collecting inputs/outputs of materials/products for each supply chain process in relation to the relevant countries and time frame (i.e. information not older than 5 years).

Two different options of data sources have been evaluated in terms of collecting the required information for the inventory analysis (details regarding this evaluation are summarized in Appendix B.2). As first option, ecoinvent (Wernet et al. 2016) is considered, a unit process life cycle inventory database commonly used in LCA studies. Following our evaluation, data from ecoinvent is not sufficient for the inventory analysis because information about specific processes, materials/products and countries along supply chains is missing and/or outdated. As a second option, complementing these data with trade data is investigated, based on the suggestion of Beylot et al. (2020), who assess the environmental impacts of European trade in a process-based LCA study. BACI (Gaulier and Zignago 2010) is therefore consulted, a database reporting country-specific material/product-level trade data in the form of physical amounts (in kg) and monetary values (in $) for material/product categories described with 6-digit Harmonized System (HS) codes provided by the World Customs Organization (2021). BACI is seen as a particularly interesting option because it covers various trade flows along global supply chains and its data has already been used in several studies for quantifying supply chains, including for example the ones of Sun et al. (2019), Helbig et al. (2016c), Godoy León et al. (2021) and Liu and Muller (2013). Futhermore, the BACI database has also been used in for example recent LCSA studies such as the one performed by Siddhantakar et al. (2023), which is based on the GeoPolRisk approach (Gemechu et al. 2015b). Following our evaluation, the physical trade amounts included in BACI provide sufficient information for the inventory analysis. The HS codes relevant for quantifying the considered supply chains are described in Appendix B.3.

However, an issue with BACI data is the aggregation levels of material/product categories described with relevant HS codes. This aggregation issue is addressed in the present study by using global average market shares and cost-to-mass ratios, since, as shown in Appendix B.4, the use of such shares and ratios allows for estimating trade flows of specific materials/products. Adjusting the content of HS codes, however, also adds uncertainty to the results of the study.

4.1.3 Inventory analysis

The inventory analysis corresponds to the second step of the 'SPOTTER implementation procedure'. Here, at first country-specific unit processes within the product system are identified by selecting HS codes that are related to each of the inventory flows along the supply chain described in the middle part of Figure 15. A list of the selected HS codes is provided in Appendix B.3 and adjustments related to the content of these HS codes are described in File 1 of the data repository D.1.

Figure 16a illustrates the identified unit processes and their inventory flows exemplarily for one part of the supply chain. These unit processes (shown as white squares in Figure 16a) describe processes that are located in specific countries and that use specific materials/products to produce certain outputs. The inventory flows (represented by arrows in Figure 16a) constitute flows that describe the outputs of unit processes and the inputs of subsequent supply chain processes (represented by the grey squares in Figure 16a). The inventory flows of each of the identified unit processes are quantified by following the procedure described in Figure 16b. This procedure involves the seven steps illustrated with different colors in Figure 16b. The steps 1-3, which are represented with orange, light blue and yellow colors, are applied to quantify the final product flows. The steps 4-7, which are illustrated with green, red, dark blue and brown colors, are followed to quantify the materials/intermediate product flows upstream of the supply chain.

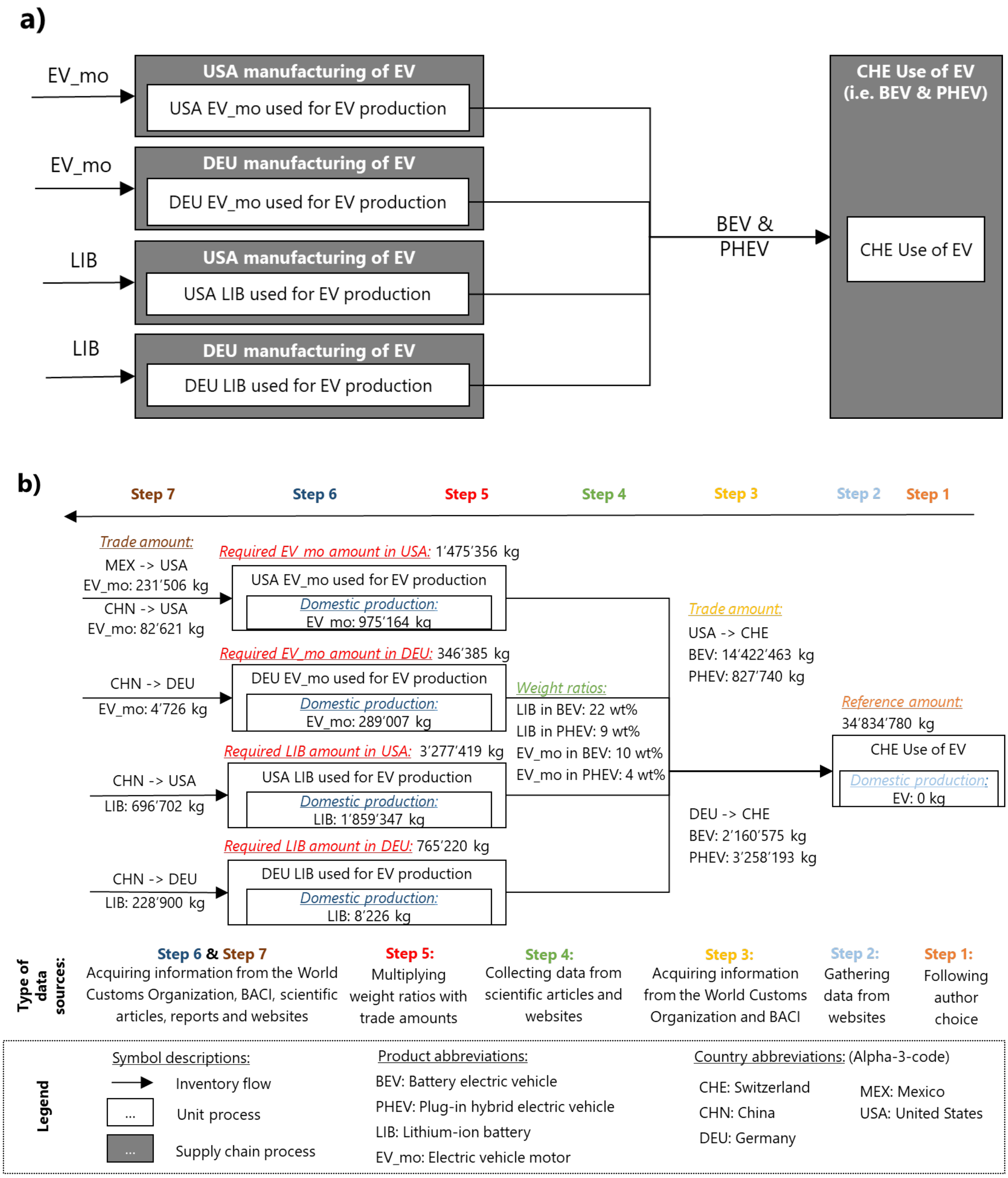

Figure 16: Illustration of the procedure used to quantify the supply chain including a) the description of unit processes for a part of the cobalt and aluminium supply chain of electric vehicles used in Switzerland in the year 2019 and b) the exemplary quantification of this part of the supply chain

The following paragraphs explain each of the seven steps presented in Figure 16b.

- Step 1: the amount of the final product is specified. This amount, which is defined by the authors of this article, corresponds to the Swiss fleet of BEVs and PHEVs in the year 2019.
- Step 2: the domestic production amount of EVs used in Switzerland is determined as 0 kg following Moresi (2018).

- Step 3: country-specific trade amounts of these EVs are identified. First, the amounts required from imports are defined by subtracting the Swiss domestic EV production amount from the amount of the Swiss EV fleet. Second, EV amounts that are manufactured in the USA, Germany and other countries and that are exported to Switzerland are determined by selecting related HS codes and applying country-specific trade distributions derived from BACI. For the extraction and formatting of BACI trade data, a python script has been developed within our work. Third, a screening of the EV flows is performed by following the third step of the 'SPOTTER implementation procedure'. Thereby all EV trade amounts that are lower than 1% of the market (i.e. trade and domestic production) are cut-off, which are for example EV flows from Italy to Switzerland with a market share of about 0.08%. Fourth, here-called 'ghost exports' of EVs, i.e. EV exports that are reported in BACI but that do not originate from actual EV production countries, are identified by for example investigating locations stated in company-specific websites. These exports supposedly refer to intermediate trades along the supply chain, which are, for simplicity reasons, neglected in this study. However, amounts of 'ghost exports' still need to be considered to maintain mass balance. Thus, these amounts are reallocated considering existing trade distributions. The trade of ~554 t of BEVs from Austria to Switzerland for example constitutes one of the 'ghost exports'. As the USA contributes by ~57% to the total import of BEVs to Switzerland, ~57% of these 'ghost exports' from Austria is added to the BEV amount traded from the USA to Switzerland.
- Step 4: global average weight ratios of LIBs and EV motors used in BEVs and PHEVs are determined. Due to data availability issues, global instead of country-specific average weight ratios are applied. Following Berjoza and Jurgena (2017), the global average weight ratio of for example LIBs used in BEVs is 22%.
- Step 5: amounts of LIBs and EV motors that are required in production countries of EVs used in Switzerland are determined. Thereby traded country-specific EV amounts defined in step 3 are multiplied with weight ratios specified in step 4. To illustrate, the LIB amount of ~3'277 t used in the USA for the production of BEVs and PHEVs traded to Switzerland is calculated as follows: Summing up the product of ~14'422 t of BEV and 22 wt% of LIBs used in these BEVs and the product of ~828 t of PHEVs and 9 wt% of LIBs used in these PHEVs.
- Step 6: domestic LIB and EV motor production amounts are defined for each country that manufactures EVs used in Switzerland as follows: First, the production amounts of LIBs and EV motors are specified for Germany, the USA and the other EV manufacturing countries. Second, these production amounts and amounts of LIBs and EV motors imports to the EV manufacturing countries are added up to country-specific market volumes of LIBs and EV motors. Third, country-specific production-to-market ratios are multiplied with the required amounts of LIBs or EV motors (see result of step 5) to determine the domestic production amounts. The domestic production amount of ~1'859 of LIBs in the USA for example is calculated by determining the production amount of LIBs in the USA (i.e. ~10'637 t) based on studies of, amongst others, Pillot (2020), Cerdas

Marin et al. (2018) and Mayyas et al. (2019) and by considering the import amounts of LIBs to the USA (i.e. ~50'705 t) reported in BACI. When country-specific production amounts are not available in the literature, which is for example the case for EV motors, these amounts are estimated by multiplying the global production amount with country-specific export distributions derived from BACI.

- Step 7: country-specific trade amounts of LIBs and EV motors are determined for the supply chain of EVs used in Switzerland. Analogously to the step 3, these trade amounts are defined by selecting suitable HS codes, applying country-specific trade distributions, following the cut-off rule and reallocating identified 'ghost exports'. In addition, trade amounts of LIBs and EV motors that are smaller than their minimum amount used in EVs are identified and reallocated. The procedure for reallocation is analogous to the one applied for 'ghost exports'. Such trade amounts may result from the use of global average weight ratios in combination with trade distributions. Finally, the flows of LIBs and EV motors relevant for the assessment over the considered time horizon (i.e. next 5 years) are identified by following the fourth step of the 'SPOTTER implementation procedure'. Thereby, the number of times that LIBs and EV motors are supposedly supplied within the next 5 years is determined based on the lifetimes of these products. This number is then multiplied with the respective trade amounts. Assuming an eight years lifetime of LIBs (Argue 2020), a 16 years lifetime of EV motors (Shrivastava 2020) and a 16 years lifetime of EVs (Nakamoto et al. 2019), it is estimated that both intermediate products are supplied once over the considered time horizon of 5 years.

All further steps to quantify the supply chain are performed analogously to the steps 4-7. The quantification of sample inventory flows from processes upstream of the ones described in Figure 16 is illustrated in Appendix B.5.

In contrast to trade amounts of raw materials and products, the trade amounts of the Co and bauxite ores are not defined based on BACI trade data but they are quantified based on production data reported by USGS (2021a, b). The export amounts of the producing countries are thereby estimated based on their production shares on the global production amount. For example, a production share of 69% on the global cobalt production is reported for Congo. Thus, 69% of the Co that is imported by the countries within the supply chain is supplied by Congo. Production data reported by USGS instead of BACI trade data are used for defining the ore trade amounts because trade flows of ores may not or only insufficiently be reported in BACI due to traceability issues of artisanal supply chains (BGR 2021). On that note, Sun et al. (2019) have highlighted that trade flows of Co ores from Congo, the country extracting the highest amounts of Co worldwide, have not been included in the trade data reported by BACI.

The completely quantified supply chain as well as the specific data types and sources used for the quantification are described in File 2 of the data repository D.1.

4.1.4 Impact assessment

The impact assessment is performed in accordance with the fifth step of the 'SPOTTER implementation procedure', where overall impact scores for the product system (PS) and bottleneck scores are defined. These overall impact scores are calculated by the sum of all bottleneck scores for the individual inventory flows as shown in Equation (9).

The bottleneck scores refer to supply bottlenecks along the supply chain. These scores are calculated by multiplying the inventory flow amount with respective CFs as shown in Equation (8). As explained in section 3.2.2, these CFs describe cause-effect chains between the six events and two impacts of supply disruption listed in section 4.1.2. Figure 17 shows the thus analyzed events and impacts exemplarily for the extract of the supply chain comprising the flow of Co powder from China to the Republic of Korea.

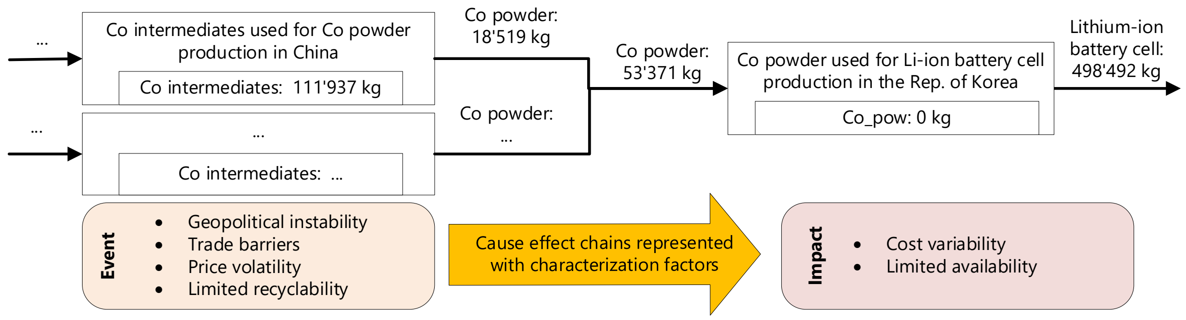

Figure 17: Outline of considered cause-effect chains along the supply chain
illustrated for the example of supply disruption events and impacts for the cobalt (Co) powder flow from China to the Republic of Korea

Just as demonstrated in Figure 17, CFs are applied to represent cause-effect chains between supply disruption events and impacts for each unit process along the Co and Al supply chains of EVs used in Switzerland. The applied CFs are calculated based on the following four basic indicators: (i) *indicator for supply disruption event over a period (EI*t)*, (ii) *indicator for supply diversity (DI)*, (iii) *indicator for vulnerability to physical shortage (PVI)* and (iv) *indicator for economic importance or economic damage (EVI)*. *EI*t* and *DI* are summarized in an *indicator for supply disruption probability over a period (PI*t)*. As explained in section 3.2.3, the values of the PIs are then consistently scaled based on a min-max-scaling to allow for an aggregation of impact scores calculated for the individual supply disruption events into the two impact categories *cost variability* and *limited availability*.

These four indicators used to calculate the CFs are defined differently for the individual events and impact categories (see Figure 13). Table 7 illustrates how these indicators are defined and quantified in the different cases exemplarily for the Co powder flow described in Figure 17.

Table 7: Quantification of indicators used to calculate characterization factors
presented exemplarily for the cobalt powder (Co_pow) flow illustrated in Figure 17. Because indicators for economic resource depletion and child labor restrictions are not described in the example given in Figure 17, they are quantified based on cobalt resource (Co_res) extraction in Congo (COD) and cobalt ore (Co_ore) flows from Congo, respectively.

a) Indicators for supply disruption events (EIs)

Indicator		Definition and quantification	Data sources
Indicators for country-specific events	Indicator for depletion of economic resource (ERD)	$ERD_{Co\_res,COD} = \frac{extr_{Co\_res,COD} - repl_{Co\_res,COD}}{stock_{Co\_res,COD}} = \frac{100'000\ t - 0\ t}{3'600'000\ t}$	Extraction rates (extr.) of Co_res are acquired from USGS (2021g). Replenishment rates (repl.) of metallic resources are assumed to be 0 t over the considered period (i.e. next 5 years).
	Indicator for geopolitical instability (GI)	$GI_{Co\_pow,CHN} = \frac{100 - WGI(PS)_{CHN}}{100} = \frac{100 - 38.10}{100}$	Values for the Worldwide Governance Indicator (Political Stability and Absence of Violence/Terrorism) (WGI(PS)) are acquired from the World Bank (2019).
	Indicator for child labor restrictions (CLR)	$CLR_{Co\_ore,COD} = (CLI_{Co\_ore,COD} * 0.2) = (5 * 0.2)$	Values for the indicator of child labor risk (CLI) in the sector of mining of metal ore (i.e. the sector related to Co_ore production in the Social Hotspot Database) are acquired from Benoit Norris et al. (2019).
	Indicator for trade barriers (TB)	$TB_{Co\_pow,CHN} = \frac{100 - TABI_{CHN}}{100} = \frac{100 - 86.5}{100}$	Values for the Trading Across Borders Indicator (TABI) are acquired from the World Bank (2020).
Indicators for global events	Indicator for price volatility (PV)	$market\ price_{Co\_pow} = \frac{global\ cost_{Co\_pow}}{global\ mass_{Co\_pow}}$ $PV_{Co\_pow} = \frac{highest\ market\ price_{Co\_pow}\ (last\ 3\ years)}{lowest\ market\ price_{Co\_pow}\ (last\ 3\ years)} = \frac{376\ ^{\$}/_{kg}}{89\ ^{\$}/_{kg}}$	Global costs and mass of Co_pow flows over the last three years are acquired from BACI (Gaulier and Zignago 2010).
	Indicator for limited recyclability (LR)	$LR_{Co\_pow} = 100\% - EoL\ RR_{Co\_pow} = 100\% - 32\%$	The End-of-Life recycling rate (EoL RR) of Co_pow used in LIBs is acquired from Church and Wuennenberg (2019). EoL RR of Al is 90% according to The Aluminium Association (2021).

b) Indicator for supply disruption event period (t)

Indicator	Definition and quantification	Data sources
Indicator for event duration (t)	t = 5 years	t is assumed equal to the considered time horizon, unless specific information about the expected event duration is available.

c) Indicators for supply diversity (DIs)

Indicator	Definition and quantification	Data sources
Indicator for resource concentration	$DI_{Co\_res,COD} = 100\%$	Resource concentrations of 100% are considered in the SPOTTER approach (see explanations in section 3.2.3)
Indicator for market concentration (used in combination with indicators for country-specific events)	$weight\%(Co\_pow\ in\ EV) = 28\%$ $market_{Co\_pow,KOR} = production_{Co\_pow,KOR} + import_{Co\_pow,KOR}$ $DI_{Co\_pow,CHN,KOR} = \frac{import_{Co\_pow,CHN,KOR}}{market_{Co\_pow,KOR}} = \frac{121'994\ kg}{0\ kg\ +\ 1'999'538\ kg}$	Co_pow import amounts are acquired from BACI (Gaulier and Zignago 2010) and Co_pow production amounts are defined based on USGS (2021g). These import and production amounts are multiplied with the weight ratio (weight%) of Co_pow used in EVs, which is estimated based on data from Tsiropoulos et al. (2018) and Petavratzi et al. (2019).
Indicator for production concentration (used in combination with indicators for global events)	$HHI_{Co\_pow} = \left(\frac{production_{Co\_pow,CHN}}{production_{Co\_pow,global}}\right)^2 + \sum_n \left(\frac{production_{Co\_pow,n}}{production_{Co\_pow,global}}\right)^2$ $DI_{Co\_pow} = normalized\ HHI_{Co\_pow} = \frac{(HHI_{Co\_pow}) * 1/n}{1 - 1/n} = \frac{0.48 * 1/15}{1 - 1/15}$	Co_pow production amounts and the number of production countries (n) are acquired from USGS (2021g).

d) Indicators for vulnerability to physical shortage (PVIs)

Indicator	Definition and quantification	Data sources
Indicator for vulnerability to physical shortage (PVI)	$weight\%(Co\_pow\ in\ EV) = 28\%;$ $weight\%(Co\ in\ Co\_pow) = 100\%$ The in-use stock of Co_pow is calculated by adding up the past production amounts of Co_pow used in LIBs over the LIB lifetime. $PVI_{Co\_pow} = \frac{production_{Co\_pow}}{(in\_use\ stock_{Co\_pow})^2} = \frac{36'475'332\ \frac{kg}{year}}{(123'711'460\ kg)^2}$	Current and past Co_pow production amounts are acquired from USGS (2021a, b, d, e). Co_pow production amounts are multiplied with the weight% that is estimated in Table 7c). The lifetime of LIBs, in which Co_pow are used, is defined using data from Argue (2020).

e) Indicators for economic importance or economic damage (EVIs)

Indicator	Definition and quantification	Data sources
Indicator for economic importance (used for analysis of cost variability (CV))	The costs of Co_pow in the supply chain ($cost_{Co\_pow,supply\ chain}$) is calculated by the sum of the following two factors (i) all Co_pow flow amounts (e.g. $m_{Co\_pow,Cell,CHN,KOR}$) multiplied with their respective cost-to-mass ratio (e.g. $\frac{cost_{Co\_pow,CHN,KOR}}{mass_{Co\_pow,CHN,KOR}}$) and (ii) the domestic production amounts of Co_pow (e.g. $production_{Co\_pow,KOR}$) multiplied with the global cost-to-mass ratio (i.e. $\frac{cost_{Co\_pow,global}}{mass_{Co\_pow,global}}$) $EVI(CV)_{Co\_pow,Cell,CHN,KOR} = \frac{m_{Co\_pow,Cell,CHN,KOR} * \frac{cost_{Co\_pow,CHN,KOR}}{mass_{Co\_pow,CHN,KOR}}}{cost_{Co\_pow,supply\ chain}} = \frac{18'519\ kg * \frac{4'106'066\ \$}{99'392\ kg}}{3'954'741\ \$}$	The Co_pow and lithium-ion battery cell (Cell) flows as well as the domestic production amounts and trade amounts of Co_pow are determined following the procedure described in section 4.1.3. Data for the cost-to-mass ratios of Co_pow and Cells are acquired from BACI (Gaulier and Zignago 2010).
Indicator for economic damage (used for analysis of limited availability (LA))	The revenue of Cells affected by supply disruptions of Co_pow is determined by the cost of Cells traded from KOR to any other country i. This cost is additionally multiplied with 1 minus the share of revenue that originates from domestic production, when events are analyzed for which domestic production is considered risk-free (i.e. geopolitical instability, trade barriers and child labor restrictions). The cost of Cells in the supply chain (i.e. ($cost_{Cell,supply\ chain}$) is calculated analogously to the $cost_{Co\_pow,supply\ chain}$, for which the calculation is shown above. $EVI(LA)_{Cell,KOR} = \frac{\sum_i \left(m_{Cell,KOR,i} * \frac{cost_{Cell,KOR,i}}{mass_{Cell,KOR,i}}\right) * \left(1 - \frac{production_{Co\_pow,Cell,KOR}}{market_{Co\_pow,Cell,KOR}}\right)}{cost_{Cell,supply\ chain}} = \frac{21'603'519\ \$ * 100\%}{50'385'459\ \$}$	

Material/product abbreviations: Cell: Cell of lithium-ion traction battery, Co_ore: Cobalt ore, Co_pow: Cobalt powder, Co_res: Cobalt resource, EV: electric vehicle, LIB: Lithium-ion traction battery; country abbreviations: COD: Democratic Republic of the Congo, CHN: China, KOR: Republic of Korea

The indicators that are required for the calculation of all other CFs are defined analogously to the examples given in Table 7. Respective indicator data and data sources are found in File 3 to File 11 of the data repository D.1. Note that the data to quantify the indicator for child labor restrictions can only be made available on condition that a suitable license for the Social Hotspot Database has been purchased.

As explained in section 3.2.3, two issues are important regarding the indicator definitions are: On the one hand, the *DI* values need to be defined differently in case of country-specific and global events. On the other hand, the *PI* and *EVI* values are context dependent, as their equations involve a case-specific scaling procedure (see *PI*) or include case-specific elements (see *EVI*). For the examples described in Figure 17, these elements are $m_{Co\_pow,Cell,CHN,KOR}$, $cost_{Cell,supply\ chain}$ and $cost_{Co\_pow,supply\ chain}$. The values of the *PI* and *EVI* thus need to be newly defined for each case study.

After all EIs, DIs, PVIs and EVIs have been quantified, the individual impact scores are calculated. Equation (20) demonstrates the calculation of an impact score for one of the examples shown in Figure 17, where cost variability (CV) of a Co powder (Co_pow) flow is caused by geopolitical instability (GI) in China (CHN) and affects the LIB cell (Cell) production in the Republic of Korea (KOR). The related inventory flow amount is defined in File 2 of the data repository D.1 and the related indicator values are provided in Table 7.

$$\begin{aligned}
\boldsymbol{CV\ score(GI)_{Co_pow,Cell,CHN,KOR}} &= \left(\boldsymbol{m_{Co_pow,Cell,CHN,KOR}}\right) * \left(\boldsymbol{GI_{Co_pow,CHN} * t}\right) * \\
&* \left(DI_{Co_pow,CHN,KOR}\right) * \left(PVI_{Co_pow}\right) * \left(EVI(CV)_{Co_pow,Cell,CHN,KOR}\right) = \\
\left(m_{Co_pow,Cell,CHN,KOR}\right) &* \left(\frac{100 - WGI(PS)_{CHN}}{100} * t\right) * \left(\frac{import_{Co_pow,CHN,KOR}}{market_{Co_pow,KOR}}\right) \\
&* \left(\frac{production_{Co_pow}}{\left(in_use\ stock_{Co_pow}\right)^2}\right) * \left(\frac{m_{Co_pow,Cell,CHN,KOR} * \frac{cost_{Co_pow,CHN,KOR}}{mass_{Co_pow,CHN,KOR}}}{cost_{Co_pow,supply\ chain}}\right) \\
&\approx 1.6 * 10^{-6}
\end{aligned} \tag{20}$$

Once all impact scores have been calculated, overall supply disruption impacts are determined by summing up all impact scores per impact category (see Equation (9)) and supply disruption hotspots are defined by identifying the biggest supply bottlenecks (see Equation (8)).

A python script that has been developed within our work and the open source software Brightway2 (Mutel 2017) have been used to make all the calculations required for this case study.

4.1.5 Interpretation

Two kinds of hotspots, i.e. hotspots per impact category (e.g. hotspots of cost variability) and hotspots per individual supply disruption event and impact category (e.g. hotspots of cost variability due to geopolitical instability), are defined. The first kind of hotspots is defined by considering all bottleneck scores that are higher than 1% of the overall impact per impact category. The second kind of hotspots is defined by considering all bottleneck scores that are higher than 1% of the overall impact per supply disruption event and impact category. The threshold of 1% is set following the "Guide for interpreting life cycle assessment results" published by Schau et al. (2016), where contributions above 1% of the total impact are highlighted as relatively high.

4.2 Results and discussion

4.2.1 Locations of supply disruption hotspots per impact category

Figure 18 and Figure 20 use global maps as presentation format to illustrate geographical locations of the identified supply disruption hotspots. The two maps shown in Figure 18 display impacts higher than 1% of the overall impact scores for cost variability and limited availability (i.e. impacts referred to as first kind of hotspots in section 4.1.5).

Within the global maps, locations of hotspots due to country-specific supply disruption events are indicated with solid arrows that range from countries, in which the event occurs, to the countries affected by the supply disruption. Conversely, locations of hotspots due to global events are marked with vertical, dashed arrows that reach from the top or the bottom of the map to the affected countries. The magnitude of the impacts is described by the size of a circle placed on top of the affected country. Locations of supply disruption events are indicated with red crosses.

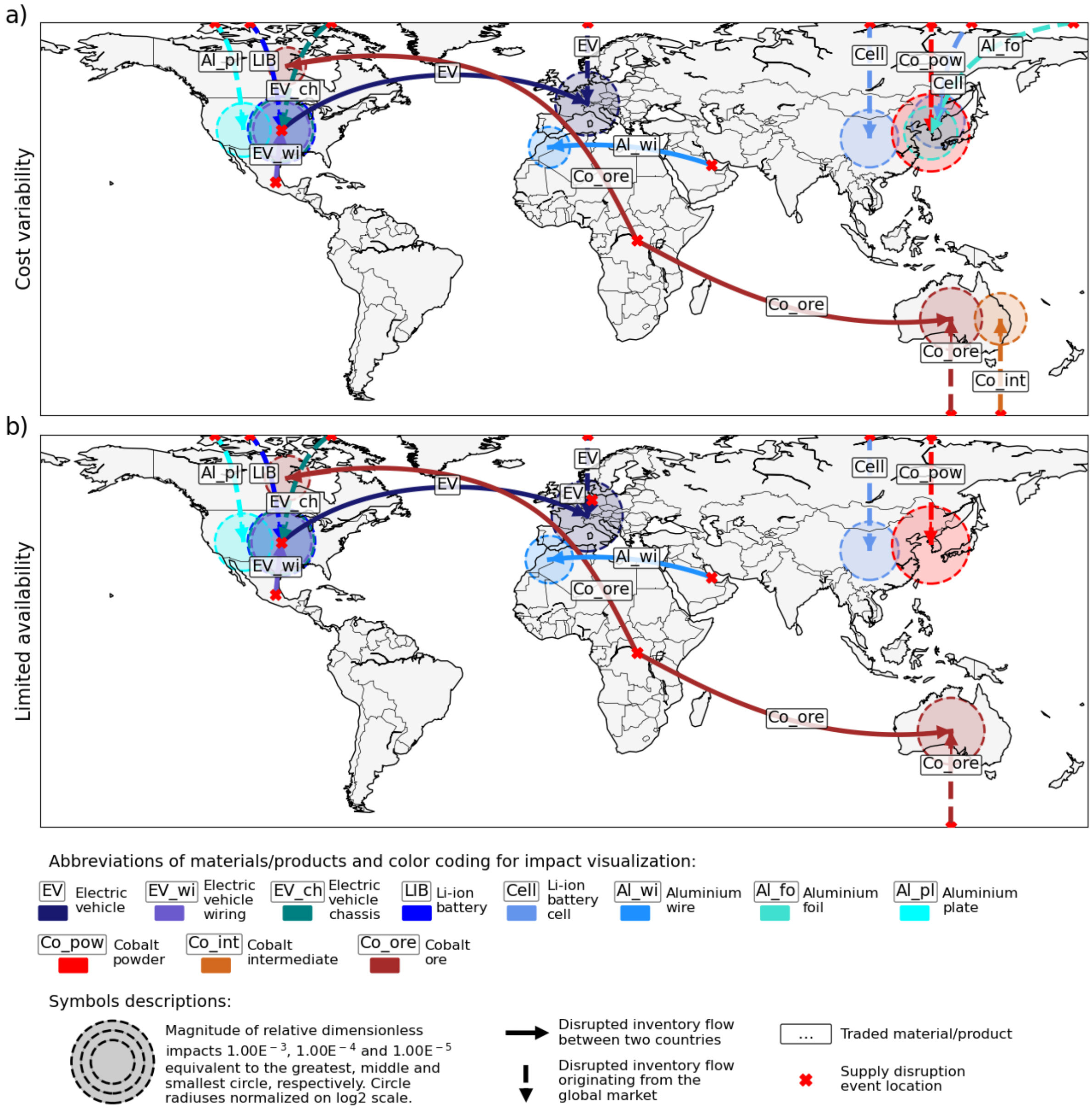

Figure 18: Hotspots of a) cost variability and b) limited availability
along the cobalt and aluminium supply chain of electric vehicles used in Switzerland. Hotspots are visualized with red/brown color shades for upstream stages of cobalt supply and with blue/purple color shades for downstream supply chain stages.

Three-quarters of the hotspots presented in Figure 18 (i.e. 12 out of 16) are hotspots of both cost variability and limited availability. Two examples are impacts of disrupted EV supply from the USA to Switzerland and impacts of disrupted LIB cell supply from the global market to China. This suggests that there is a correlation between impacts covered by the two categories. Such a correlation has also been identified by Frenzel et al. (2017), who state that particularly large effect sizes of price hikes lead to severe physical disruptions. Information on effect sizes specific to price hikes and physical disruptions would thus allow for assigning impacts to cost variability or limited availability, but as also stated by Frenzel et al. (2017), such information is still widely missing. Another explanation for the correlation between the impacts is related to the calculations of impact scores. Calculations of scores for the two impact categories differ in only one of four indicators, i.e. the indicator for economic importance or damage. Hence, when values of the other three indicators are pivotal for the impact assessment, the calculated impact scores inevitably refer to impacts of both categories.

The remaining quarter of the hotspots are specific to cost variability or limited availability. Hotspots related to cost variability indicate flows of materials/products with specifically high economic importance for the product system. The flow of LIB cells from the global market to Korea is an example of such a flow. Conversely, hotspots related to limited availability suggest relatively large affected revenues. The revenue related to EVs traded from Germany to Switzerland is an example of such an affected revenue.

Several hotspots (i.e. 12 out of 16) refer to the supply of intermediate or final products. These hotspots often indicate supply risks along the supply chains of one specific end-product manufacturer. For example, potential disruptions of EV wiring supply from Mexico to the USA only affect the supply chains of US EV manufacturers. In this case, the restructuring of the supply chain by importing EVs also from other countries than the USA may be a viable risk mitigation measure. In the case of supply risks indicated with the remaining hotspots, supply chain restructuring may not be useful, because the described potential disruptions of raw materials and minerals supply often affect simultaneously the supply chains of several end-product manufacturers. For example, potential disruptions of Co ore supply from Congo to Australia supposedly affect the supply chains of EVs produced in Germany and the USA. Measures suitable for dealing with these and other supply risks identified with our hotspot analysis are suggested in section 4.2.5.

4.2.2 Relative magnitude of hotspots

While the maps shown in Figure 18 are useful to represent the locations of the hotspots, they do not allow for clearly illustrating the relative magnitude of specific hotspot scores and thus make it difficult for decision-makers to identify the most relevant hotspots. To define the relative magnitude of hotspots, individual hotspot scores calculated for each of the impact types following Equations (9) and (11) to (15) are divided by the overall impact scores listed in Table 8.

Table 8: Overall impact scores for the considered impact types.
For illustration purposes, the presented impact scores are multiplied by a factor of 1000.

Impact category	Supply disruption events	Impact score [dimensionless]
Cost variability	Geopolitical instability	0.630
	Trade barriers	0.289
	Child labor restrictions	0.170
	Price volatility	1.475
	Limited recyclability	0.430
	Total of all events	**2.994**
Limited availability	Geopolitical instability	1.177
	Trade barriers	0.484
	Child labor restrictions	0.265
	Price volatility	1.312
	Limited recyclability	0.360
	Resource depletion	0.208
	Total of all events	**2.807**

The pie charts shown in Figure 19 present the shares of the hotspot scores for cost variability and limited availability, for illustration purposes, aggregated on the level of the affected material/products. Impacts that are not classified as hotspots (i.e. represent less than 1% of the overall impact) are summed up in the category "Rest" (beige color). The hotspot shares related to individual flows of the materials/products are visualized in Appendix B.6, where these shares are presented for hotspots per impact category and hotspots per individual supply disruption event and impact category in stacked bar charts.

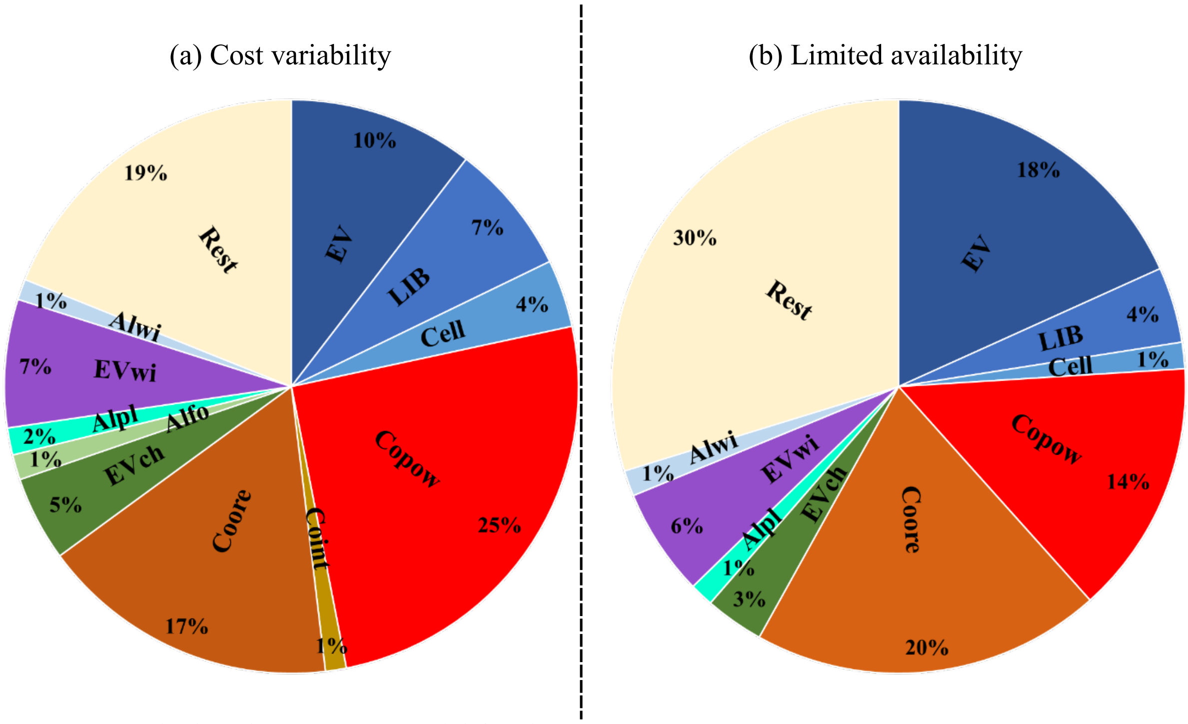

Figure 19: Magnitude of hotspots for materials/products utilized along the cobalt and aluminium supply chains of electric vehicles used in Switzerland considering (a) cost variability and (b) limited availability. Abbreviations for the materials/products are explained in Figure 18.

Overall, the highest contributions to overall impacts are associated with hotspots related to the supply of EVs, EV wiring, traction batteries and their cells, Co powder as well as Co ore. The shortage of wiring and traction batteries for car manufacturers, the potential cost increases of Co powder as well as the insecurity related to the supply of Co ore from Congo have been highlighted in various media (CBVC 2022; Jolly 2022; King 2018; Manley et al. 2022). Identified hotspots indicated with the highest contributions in Figure 19 are thus in line with current or predicted future concerns of supply chain managers. The particularly high contributions of EV impact to the overall impacts (around 10% in case of cost variability and around 18% in case of limited availability) may however seem odd since EV shortage is not considered a big issue in the real world. An explanation of this difference in perception is that our study considers EVs as the only available vehicle type and disregards the purchase of conventional vehicles. As more conventional vehicles than EVs are currently on the market and in use in Switzerland, considering conventional vehicles as an alternative to EVs would certainly lower the physical availability constraints and thus the impact of EVs. However, following the Clean Vehicles Directive implemented by the European Parliament and Council (2019) regarding the phasing out of petrol and diesel cars by 2035, purchasing conventional vehicles does not really describe a reasonable alternative in the future.

4.2.3 Locations of supply disruption hotspots per event and impact category

The eleven maps shown in Figure 20 display a disaggregated version of Figure 18, which represents impacts specifically for the individual events (i.e. impacts referred to as second kind of hotspots in section 4.1.5). The related impact scores are higher than 1% of the scores for cost variability and limited availability caused by the individual supply disruption events.

Figure 20a-f and Figure 20k suggest that supply chains may often be disrupted due to events originating in Asian, African or other developing countries and affecting Western economies. The identified hotspots are for example related to material/product flows from China, Korea, Mexico, Guinea and Congo to the USA, Canada, Germany and Poland. Reasons for these hotspots are the high probability of occurrence of supply disruption events in developing countries (Benoit Norris et al. 2019; World Bank 2019, 2020), the concentrated trade of materials/products in these countries (Seong et al. 2022), and/or the high dependency of Western economies on the supply of these materials/products (World Economic Forum 2016).

As shown in Figure 20a-f, some inventory flows may be disrupted due to the occurrence of multiple events. In some cases, the likelihood of the occurrence of different events in the same country is particularly high, as seen for example by the events causing potential disruptions of Co ore supply from Congo to Australia. The World Bank (2019, 2020) and Benoit Norris et al. (2019) rate the probability of geopolitical instability, trade barriers and child labor restrictions for Congo as relatively high. In other cases, the supply concentration or vulnerability factors have a high influence on the impact, as seen in the example of risks related to EV wiring supply from Mexico to the USA. The probability that supply disruption events occur in Mexico is rated as relatively low by the World Bank (2019, 2020), but the influence of market concentration and economic importance or damage is relatively high in this example.

The previous example highlights that some impacts constitute hotspots because related supply disruption events have relatively large consequences but rather low probabilities of occurrence. The identified hotspots related to the EV supply from Germany to Switzerland are such an example, as the occurrence of geopolitical instability and trade barriers is seen as rather unlikely for Germany but the German EV imports are considered to be of high economic importance. Furthermore, the hotspots related to the Al wire supply are another example of hotspots, which might be surprising as they indicate supply disruption risks that, in times of several extensive disruptions along the EV supply chains (see examples in section 4), do not manifest in the real world. The reasons why they have been identified as hotspots are relatively high probability of geopolitical instability and trade barriers in Bahrain, the Al wire market concentration on the flow from Bahrain to Morocco as well as the high economic importance/damage related to the disruption of this flow.

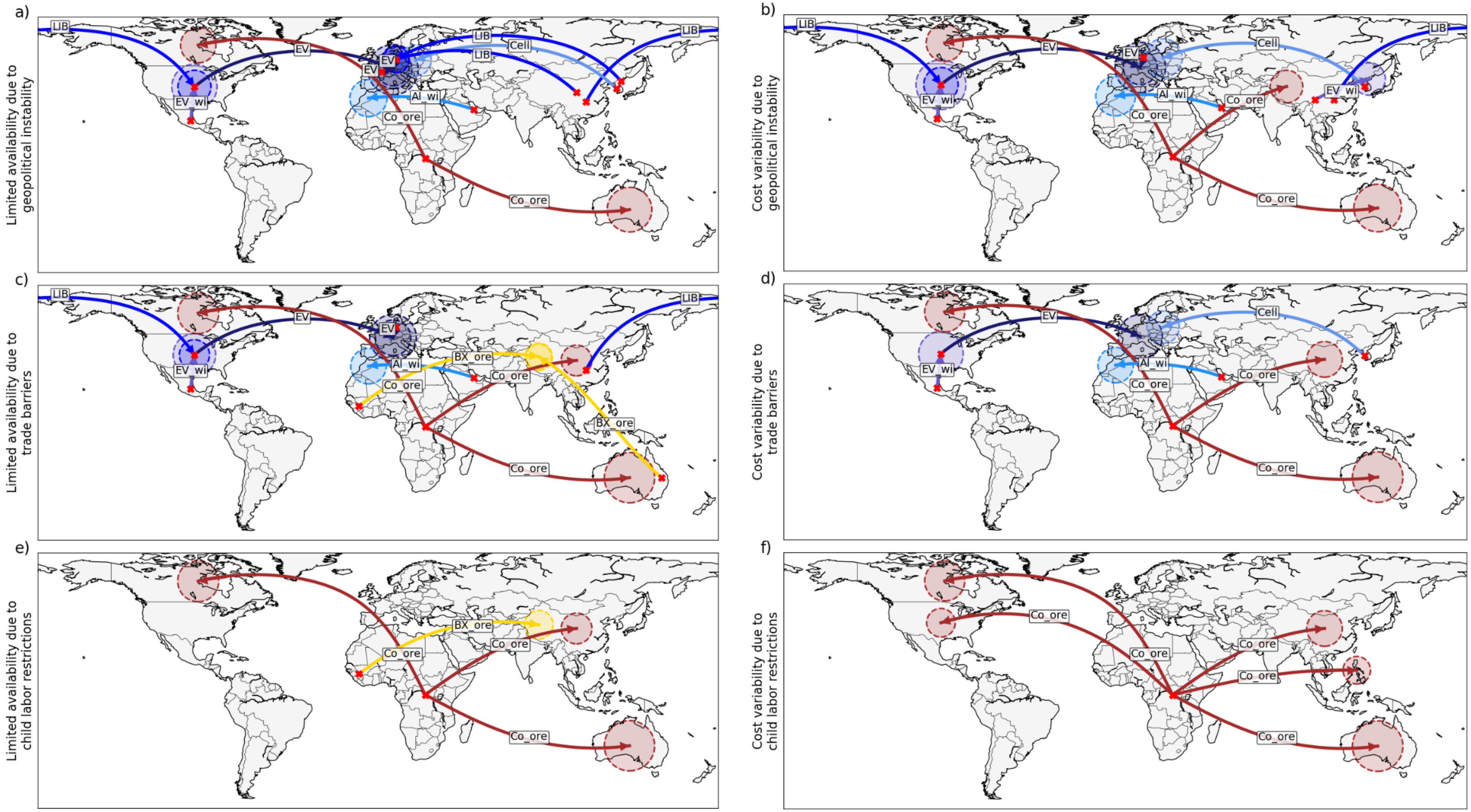

Figure 20: Hotspots of limited availability and cost variability due to individual events considering six different events along the cobalt and aluminium supply chain of electric vehicles used in Switzerland. Hotspots are visualized with red/brown color shades for upstream stages of cobalt supply, with yellow color shades for upstream stages of aluminium supply and with blue/purple color shades for downstream supply chain stages.

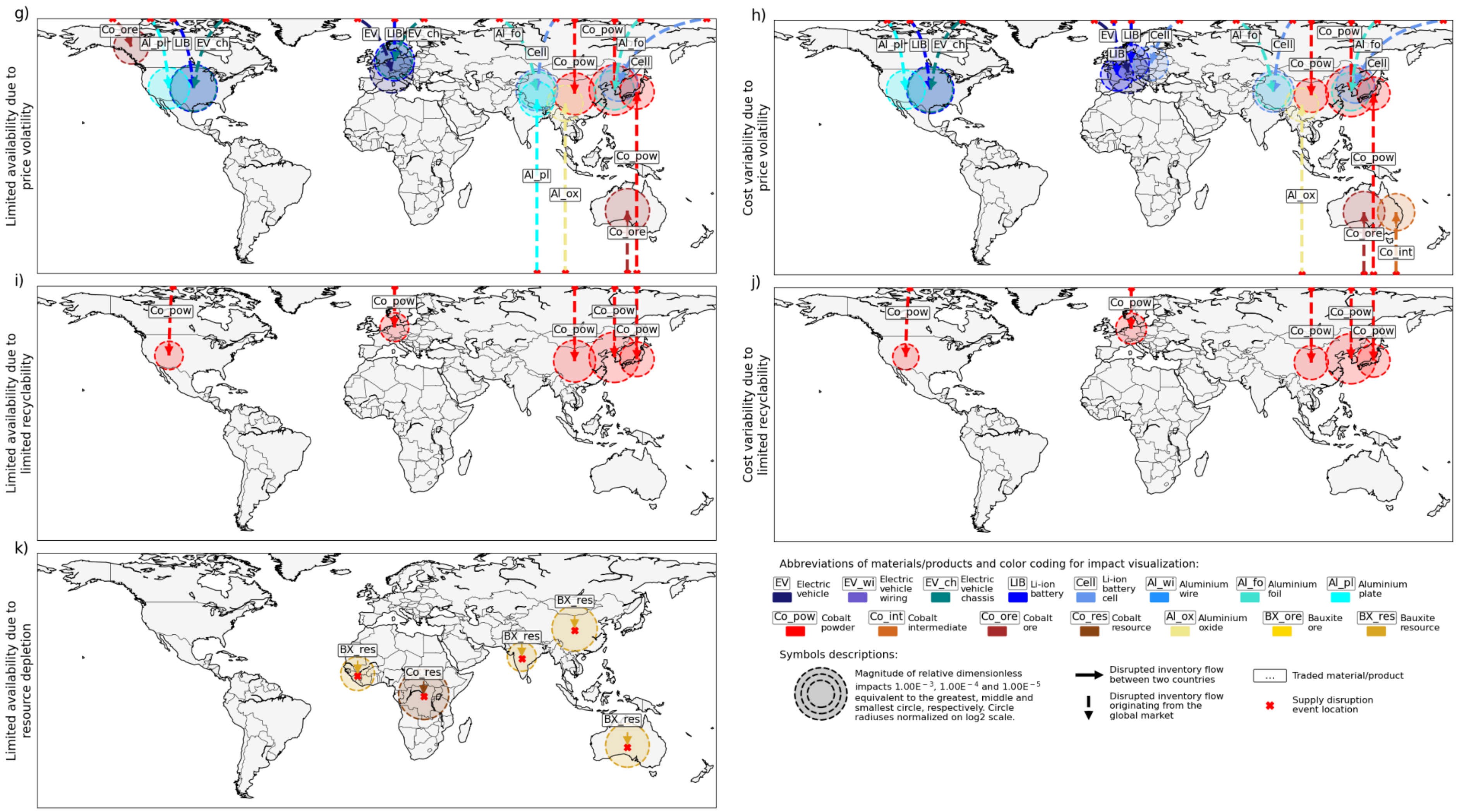

Figure 20 (continued)

The majority of hotspots due to geopolitical instability and trade barriers are defined by impacts of intermediate and final products (see Figure 20a-d). One reason is related to the fact that only impacts of traded materials/products are evaluated for these two events, while domestic production is considered "risk-free". Indeed, the impacts of Co powder and Al unwrought are low because both metals are mainly domestically refined (Sauvage 2019; van den Brink et al. 2020). Conversely, intermediate/final products such as LIBs, EV wiring and EVs are frequently traded because specialized production processes are often spread over different countries. Their production has become increasingly specialized in order to enhance productivity, competition and innovation (OECD 2013). In relation to such specialization, the supply of intermediate and final products is often concentrated in a few countries. An example is the supply of LIBs, of which 72% are produced in China according to Yu and Sumangil (2021). The supply of Co powder and Al unwrought in turn is relatively diverse following the BACI trade data, i.e. exports are distributed over different countries. As these two raw materials have thus a relatively low market concentration, their impacts are considered as comparably low. The remaining hotspots due to geopolitical instability and trade barriers refer mainly to the supply of Co ores from Congo, as stated above a particularly unreliable source, but also to flows of bauxite ores from Guinea and Australia to China.

Hotspots due to child labor restrictions (see Figure 20e and Figure 20f) are, as explained in section 4.1.2, analyzed only for the Co and bauxite ore supply in our study. These hotspots are mainly related to Co ore supply from Congo but also occur for the bauxite supply from Guinea. Benoit Norris et al. (2019) estimate very high risks of child labor for both Co and bauxite mining. The reason for the dominance of hotspots related to Co supply in Figure 20e and Figure 20f is the higher country concentration of Co mining in relation to bauxite mining indicated by the USGS (2021a, 2021c). Banza Lubaba Nkulu et al. (2018) report the potential occurrence of child labor during the widespread artisanal mining of Co ore in Congo and the U.S. Department of Labor. Bureau of International Labor Affairs. (2011) documents child labor in bauxite mining in its report, which aligns with the results of our hotspot analysis.

Hotspots due to price volatility (see Figure 20g and Figure 20h) are defined by impacts of materials/products with relatively high price variations and particularly large trade or domestic production amounts. Here, mainly Asian, European and Northern American countries are affected as large amounts of materials/products are consumed for the production and manufacturing processes in these countries. Following Figure 20g and Figure 20h, price volatilities are mostly associated with the materials/components of traction batteries such as battery cells, Al foil and Co powder. An example of a hotspot is the LIB cells used for LIB production in China, for which relatively volatile prices are seen following BACI trade data and are reported by BloombergNEF (2022a).

Hotspots due to limited recyclability of raw materials (see Figure 20i and Figure 20j) are only defined by impacts of Co powder. Co powder has a lower recycling rate than Al unwrought according to Church and Wuennenberg (2019) and The Aluminium Association (2021). By following the min-max-scaling procedure described in Equation (19), related supply disruption probabilities are rated with 100% for Co powder and 0% for Al unwrought. All impacts caused by limited recyclability of Al unwrought are thus evaluated as zero. The identified hotspots are concentrated in Asia, as Co powder is mainly used there for the production of traction batteries.

Hotspots due to resource depletion (see Figure 20k) are located in countries, where the extraction-to-resource stock ratios are relatively high. Co resources extracted in Congo and bauxite resources extracted in China and Australia thus describe the major hotspots. However, while the use of the here-applied indicator is suggested by Berger et al. (2020) to assess impacts of resource depletion on the product system, the related hotspots should generally be treated with caution, as resource depletion within the next five years is rather unlikely. Jowitt et al. (2020) for example have highlighted that global resource stocks of Co and bauxite have not significantly decreased in relation to the production over the last 50 years. The intention behind presenting these hotspots is thus not to inform about the unavailability of resources but to highlight the locations in the supply chain where price increases for resource extraction processes would have the highest impacts on the product system. This issue could probably be described more appropriately with other indicators than the extraction-to-resource stock ratios, but, as the review of Sonderegger et al. (2020) shows, such indicators are currently not available in the literature.

4.2.4 Comparison with existing studies

The studies performed by Cimprich et al. (2017, 2018) and Lütkehaus et al. (2022) have already analyzed supply disruption hotspots for EVs using criticality assessment approaches integrated into the LCSA framework. While their studies focus particularly on the supply of different raw materials, our study evaluates the full Co and Al supply chains of EVs. Furthermore, in contrast to our study, the supply of cobalt is not considered in their supply chain analysis. Finally, our study represents the country-specific variabilities of impacts on flows along the supply chain, while the studies of Cimprich et al. (2017, 2018) and Lütkehaus et al. (2022) do not illustrate such variabilities but only describe the impact on the supply of the specific raw material. For example, the hotspots for cobalt ore supplied from Congo to Australia and cobalt ore supplied from Congo to Canada (see Figure 20a-f) could thus not have been identified in their studies. Consequently, the results of the studies conducted by Cimprich et al. (2017, 2018) and Lütkehaus et al. (2022) are hardly comparable with the results of our study.

Supply bottlenecks (i.e. supply disruption hotspots) along EV supply chains have also been identified by studies performing criticality assessment outside of the LCSA framework. These studies inevitably lack the benefits of assessments within this framework that are described in section 1.3. Examples are studies conducted by Moss et al. (2013) and Blagoeva et al. (2016), which just as we did in our study (see Figure 18 and Figure 20), highlight an instability of the cobalt supply. However, in contrast to our study, these two studies only analyze the raw materials supply. The EU Foresight Study developed by Bobba et al. (2020) in turn has identified supply bottlenecks at several stages of the supply chain. This study considers, amongst others, the supply chains of batteries and traction motors. The EU Foresight Study as well as our study have for example identified comparatively big supply bottlenecks associated with LIBs and LIB cells exported by China and other Asian countries. However, several other supply disruption hotspots that have been identified in our study do not occur in the EU Foresight Study. Examples are the supply disruption hotspots defined by impacts related to Al wire, EV wiring and bauxite ore supply (see Figure 20a-f). Reasons for the identification of additional hotspots in our study may be: on the one hand, the SPOTTER approach used in our study allows for identifying impacts related to material/product flows between specific countries along the global supply chains of Switzerland, while the approach applied for the EU Foresight Study allows for identifying supply bottlenecks related to the EU imports of materials/products. On the other hand, our study represents bottleneck scores for the individual materials/products, while the EU Foresight Study presents aggregated bottleneck scores encompassing scores for all considered raw materials, processed materials, components or assemblies, respectively.

4.2.5 Possible risk mitigation measures

Last but not least, possible measures for mitigating the supply risks identified with the support of our hotspot analysis (see preceding sections) are listed here. As short-term impacts along Swiss supply chains have been assessed in our study, the proposed measures are targeted towards the designers of the Swiss resource strategy for the next 5 years as well as towards Swiss retailers of EVs. The suggested mitigation measures have been identified by making use of the list of generic risk mitigation measures presented in the report of Spörri et al. (2017).

The identified supply risks are split into three different groups. The first group of the identified supply risks refers to potential disruptions of the EV supply. These disruptions could result from price volatilities as well as geopolitical instabilities and trade barriers in the USA and Mexico affecting the supply of EVs and EV components. As mentioned in section 4.2.2, supply disruptions of EVs have so far not been a big concern, as conventional vehicles could be purchased instead of EVs. However, when EVs are increasingly implemented as replacements for conventional vehicles as it is predicted by for example BloombergNEF (2016), it becomes crucial to establish risk mitigation measures. Risks related to the price volatilities of EVs and EV components could thus be addressed by implementing hedging strategies. The dependency on EVs produced in the USA could be reduced by restructuring the supply chains as suggested in section 4.2.1.

The second group of the identified supply risks refers to supply disruptions of traction batteries or battery cells supplied by Asian countries as shown in Figure 20a-d. In the case of these supply risks, restructuring the supply chain may not be a viable option for risk mitigation, as these batteries are already integrated into the vehicle by EV manufacturers in various countries. Instead, policy-makers could incentivize circular economy strategies for Switzerland regarding traction battery supply by supporting related research activities and the establishment of required infrastructure as already done for example in the frame of the CircuBAT project (CircuBAT 2022). Due to the nonexistent EV production in Switzerland and the resulting complete reliance on EV imports from abroad, the Swiss industry stakeholders are limited in their possibilities to establish risk mitigation measures. However, EV producers in other countries could conclude long-term contracts with traction battery suppliers that are located in trustworthy countries such as most of the European countries (see list of national reputation ratings published by Knoema (2022)) or establish backward integration for their battery supply. As mentioned before, Swiss retailers could then restructure their supply chain by increasingly buying from more reliable EV producers.

The third group of identified supply risks refers to potential supply disruptions for EV materials/components caused by price volatilities, limited recyclability and country-specific events (i.e. geopolitical instability, trade barriers or child labor restrictions). Following Figure 18 and Figure 20, such disruptions are particularly likely along the supply chain of Co. To mitigate these risks, policy-makers could support research activities on (further) developments of the chemistry of the traction batteries aiming, amongst others, for a reduction of the battery's cobalt content. First research activities in this direction are already performed, for example, within the "SeNSE" project (SeNSE 2020). Furthermore, research on more effective recycling of critical materials such as Co from traction batteries, research that has already been initiated according to the Federal Laboratory for Materials

Testing and Research (2019), could be further supported. Finally, battery and EV producers could build up stockpiles of the most critical materials and components needed for their production process, which constitutes a measure that has also been suggested by Sprecher et al. (2017a) to tackle supply risks of critical metals in the short-term.

As shown above, our hotspot analysis allows highlighting potential supply disruptions along the full supply chain. Following the comparison between the results of our study and the ones of existing studies described in section 4.2.4, existing studies, in contrast to our study, only consider parts of the supply chain and do not inform about country-specific variabilities of impacts. Hence, some of the recommendations for risk mitigation provided in this section could not have been deduced from existing studies. For example, an effective restructuring of supply chains or conclusion of long-term contracts with producers can only be carried out when the most critical material/product flows between the different countries along the supply chain are known.

4.3 Conclusions on the assessment for electric vehicles

In this chapter, we have demonstrated the application of the SPOTTER approach for the assessment of short-term impacts of supply disruptions along the cobalt and aluminium supply chains of electric vehicles (EVs) used in Switzerland. The definition of the goal and scope, the performance of the inventory analysis, impact assessment and interpretation phases related to SPOTTER have been explained.

In the phase of goal and scope definition, the objectives, the considered events and impacts of supply disruption, the functional unit, the product system and the data requirements have been described in relation to the case study. The identification of supply disruption hotspots and the calculation of scores of overall supply disruption impacts have been defined as the objectives of the case study. *Geopolitical instability*, *child labor restrictions*, *trade barriers*, *price volatility*, *limited recyclability* and *depletion of economic resource* have been analyzed as the supply disruption events as well as *cost variability* and *limited availability* have been considered as the impact categories. The Swiss EV fleet in the year 2019 has been defined as the functional unit. The material/product flows along the cobalt and aluminium supply chain of these EVs have been depicted as the product system. Cobalt and aluminium supply chains have been considered due to the high relevance of these two metals for producing the battery and structural components of an EV and due to the rating of cobalt and bauxite as critical raw materials for the European Union. Complementing ecoinvent data with BACI trade data has been identified as a suitable option for the quantification of the supply chain.

In the inventory analysis phase, the quantification of material/product flows has been explained. Here, it has been illustrated that these flows are defined upstream along the supply chain by first defining the final product flows, then the flows of intermediate products and raw materials and finally the mineral flows.

In the impact assessment phase, the calculations of the impact scores related to each of the defined material/product flows have been explained by the example of a part of the supply chain considered for the case study.

In the interpretation phase, it has been illustrated that the impact scores higher than 1% of the overall impact, i.e. the sum of all impact scores, are interpreted as supply disruption hotspots.

The locations of the identified hotspots have been presented on global maps and the relative magnitude of these hotspots have been visualized in the form of pie charts and stacked bar charts. In general, the results of our hotspot analysis suggest that supply disruption events occur in Asian or developing countries and affect Western economies. Supply risks indicated with these hotspots are particularly high for the supply of EVs, EV wiring, traction batteries, cobalt powder and cobalt ore. More specifically, hotspots are described by impacts stemming from (i) geopolitical instability and trade barriers related to the supply of EVs from the USA, traction batteries from Asian countries and wiring from Mexico, (ii) volatile prices and limited recyclability of cobalt powder, (iii) volatile prices of traction batteries, as well as (iv) geopolitical instability, trade barriers and child labor restrictions related to the supply of Co ores from the Democratic Republic of the Congo.

At the end of the chapter, the novel contribution of the SPOTTER approach in the form of a more comprehensive analysis of supply disruption hotspots along the supply chain (compared to existing studies) has been highlighted based on the results of the presented case study. Furthermore, it has been demonstrated how these results could then facilitate the identification of suitable risk mitigation measures.

Nevertheless, certain limitations remain that need to be addressed by future research. First, there are issues concerning the quantification of event probabilities, as the currently used indicators may not adequately represent the supply disruption event (see for example the discussion regarding resource depletion indicators in section 4.2.3) or the provided scales of indicators may lead to an over- or underestimation of probabilities. To tackle these issues, the use and definition of related indicators could be refined. With regard to for example the resource depletion indicators, empirical studies in collaboration with mining companies could be performed to acquire pertinent data regarding economic resource stocks. Second, the quality of the assessment results is highly sensitive to data availability and quality. This issue could be addressed by extending databases used in criticality assessment and LCSA with more detailed material/product flow information acquired from for example relevant scientific articles or reports. Third, the relative importance of identified supply disruption hotspots has been determined based on the aggregation of bottleneck scores into overall impact scores. While a linear relationship between these bottleneck scores is assumed, which does not necessarily exist, another possibility to analyze the relative importance of hotspots would be to cross-check the results with industry experts as suggested by Schrijvers et al. (2020b).

In the here-presented study, the SPOTTER approach has been applied for a hotspot analysis on the product level. Future research could focus on performing further types of assessments with SPOTTER. One future research direction could be the identification of supply scenarios associated with comparably low supply risks by comparing the overall impact scores related to each scenario. Scenarios could for example be designed considering changes in the Swiss EV fleet or the supply situations for EVs used in other countries. Another future research direction could be to assess the impacts related to specific flows along the supply chain before and after their disruption. This would allow for an evaluation of whether the supply chain has become more resilient through the response to supply disruptions.

While the focus of the presented case study has been on identifying supply disruption impacts of the Co and Al supply chains of EVs, in the next step, the application of SPOTTER will be extended towards an assessment on a sectoral level. The objective of such an assessment will be to analyze hotspots along the supply chains of all the critical raw materials used within technologies relevant to different sectors and to compare impacts between different technologies.

"Supply Chain is like nature, it is all around us"

~ Dave Waters

5. Short-term assessment of the Swiss mobility, energy and ICT sectors

Established and emerging technologies[11] used within the Swiss mobility, energy and ICT sectors have important functionalities for the Swiss economy and high strategic relevance in terms of complying with GHG emission targets (Swiss Federal Council 2021b, 2022). At the same time, the complex supply chains for these technologies are particularly vulnerable to supply disruptions occurring anywhere around the world. Just recently, the price increases, supply shortages and sanctions, which have been a result of the Russian-Ukrainian war, and the lockdown, which has been imposed due to the COVID-19 pandemic, have caused significant losses in imports and exports along these supply chains according to Minsch (2022) and Büchel et al. (2020). Following IEA (2021), further supply disruptions can be expected in the next few years, as relevant technologies commonly involve several raw materials that are rated as critical for the EU (European Commission 2023).

To avoid significant declines in Swiss trade as well as to guarantee a successful implementation and upscaling of clean, innovative technologies in Switzerland, it is important to anticipate potential disruptions along relevant supply chains and utilize technologies associated with comparably low supply risks. Thus, supply bottlenecks need to be analyzed and potential supply disruption impacts between relevant technologies that fulfill the same functions need to be compared. A possibility to perform such bottleneck analyses and impact comparisons is the use of criticality assessment approaches (Schrijvers et al. 2020b).

Spörri et al. (2017) and Kohl (2010) have used such approaches to analyze supply bottlenecks for Swiss companies. However, due to the focus on a few companies, their studies do not inform about bottlenecks in the supply chains for technologies representing entire sectors of the Swiss economy. Other studies have performed bottleneck analyses on a technology level. Examples are the studies of Moss et al. (2011, 2013) and Blagoeva et al. (2016), which focus particularly on key decarbonization technologies such as solar panels, wind turbines and EVs used in the EU. However, their studies analyze only the raw materials supply and focus on a few technologies. They thus do not allow for informing

[11] According to Rotolo et al. (2015), emerging technologies describe technologies that "have assumed increasing relevance in the context of policy making for perceived ability to change the *status quo*".

about supply disruptions along full supply chains on a sectoral level. The EU Foresight Studies developed by Bobba et al. (2020) and Carrara et al. (2023) have performed more comprehensive bottleneck analyses along supply chains for technologies used in different EU sectors (i.e. electromobility, renewable energy, energy-intensive industry, ICT, aerospace and defense sectors). However, these Foresight Studies are limited to materials/products directly imported by EU countries and thus do not include flows upstream of direct suppliers.

Regarding impact comparisons between different technologies, the criticality studies performed by for example Helbig et al. (2016, 2018) have compared the impacts between different solar panel and LIB technologies but focusing only on the supply of raw materials.

Some of the existing bottleneck analyses and impact comparisons have also been integrated into the LCSA framework, because such integration has amongst others, the benefit of avoiding burden-shifting between supply disruption impacts and environmental impacts (see a description of benefits in section 1.3). Bach et al. (2017b) and Arendt et al. (2020) for example have performed such integrated assessments analyzing the bottlenecks for the raw material supply of the German and European economies. However, their assessments focusing on raw materials only and performed on the level of the overall economy do not allow for identifying bottlenecks specifically related to the supply chains for key technologies. Cimprich et al. (2017) and Sun et al. (2021) in turn have analyzed bottlenecks on the technology level and compared overall impacts for internal combustion engine cars (ICECs) and battery electric cars (BECs) used in the EU and China. However, their studies are not suitable for representing supply risks along full supply chains of entire sectors, as they focus on raw materials supply and two specific technologies only. Tackling the issue regarding the so far missing coverage of full supply chains, the SPOTTER approach described in section 3 has been applied in a case study addressing Co and Al supply chains of electric cars used in Switzerland (see section 4). This case study indicates risks in these entire Co and Al supply chains but, due to its focus only on a specific technology, it does not allow for representing risks to supply chains within entire sectors of the economy.

This chapter is going a step further by using the SPOTTER approach for assessing short-term impacts along full supply chains for technologies representing entire sectors of the Swiss economy. Specifically, the mobility, energy and ICT sectors are considered, because, as shown in section 1.1, technologies used in these three sectors are of high economic and strategic importance for the Swiss economy and supply disruptions are likely to occur along their supply chains. Within this case study, supply bottlenecks (in the following also referred to as supply disruption hotspots) are analyzed and supply disruption impacts are compared between relevant technologies.

Through the performance of the case study presented in this chapter the following main research question is addressed:

> ***RQ4*: What are short-term impacts of potential supply disruptions along the supply chains within the Swiss mobility, energy and ICT sectors?**

To answer the main research question, the following three sub-research questions are addressed:

- ❖ *Q1*: How can material/product flows that are influential for an assessment on a sectoral level be identified and quantified?
- ❖ *Q2*: What are supply disruption hotspots along the supply chains within the Swiss mobility, energy and ICT sectors?
- ❖ *Q3*: Which key technologies used within the Swiss mobility, energy and ICT sectors are associated with comparably low supply risks?

Section 5.1 describes the methodological approach and the materials used for the performance of the hotspot analysis and the impact comparisons related to the Swiss mobility, energy and ICT sectors. In section 5.2, the results are presented, discussed and reflected in relation to existing studies as well as possibilities are suggested to mitigate the identified supply risks. In section 5.3, the resulting conclusions are summarized.

5.1 Materials and methods

5.1.1 Goal and scope definition

A short-term assessment of supply disruption impacts along supply chains within the Swiss mobility, energy and ICT sectors is performed with the SPOTTER approach. The objectives of this case study are (i) the analysis of supply disruption hotspots along supply chains for the Swiss economy (i.e. all three sectors combined) and for each of the sectors individually and (ii) the comparisons of overall supply disruption impacts between technologies that fulfill the same functions within the three sectors.

The product system considered for the hotspot analysis consists of processes along the global supply chains of all the final products and fuels listed in Table 9. The product systems considered for the impact comparison comprise supply chains of battery electric cars (BECs) and internal combustion engine cars (ICECs), solar panels and wind turbines as well as German and Chinese laptops. These technologies are compared because they are of high economic and/or strategic relevance for the Swiss mobility, energy and ICT sectors.

Table 9: Selection of fuels and final products
considered for the assessment of supply disruption impacts for the Swiss mobility, energy as well as Information and Communication Technology (ICT) sectors

Sector	Type of considered final product/fuel	Reasons for the selections/exclusions of final products and fuels
Mobility	*Final products:* • Battery electric car • Plug-in hybrid electric car • Hybrid electric car • Internal combustion engine car • Battery electric bus • Hybrid electric bus • Internal combustion engine bus • Internal combustion engine truck *Fuels:* • Petroleum oil • Natural gas, coal and uranium used for electricity production	The considered vehicle types have been selected based on information from the Federal Statistical Office (2022). To simplify the analysis, motorcycles, which account for only a small share of the Swiss vehicle fleet, are not included in the present study. The considered fuel types comprise petroleum oil used in combustion engines and electricity sources used for charging of traction batteries.
Energy	*Final products:* • Solar panels • Wind turbines • Alternating current (AC) generators • Nuclear power plant equipment • Hydro power plant equipment • Storage lithium-ion battery • Storage lead-acid battery *Fuels:* • Petroleum oil • Natural gas • Fuel wood • Natural gas, coal and uranium used for electricity production	The considered energy generation and storage equipment as well as fuel types used in Switzerland have been selected based on information from the BFE (2020a).

Table 9 (continued)

Sector	Type of considered final product/fuel	Reasons for the selections/exclusions of final products and fuels
ICT	*Final products:* • Mobile phones and tablets • Laptops • Desktop computers • Flat screen monitors • Flat screen televisions • Cathode-ray tube monitors/televisions *Fuels:* • Natural gas, coal and uranium used for electricity production	Concerning the considered ICT infrastructure, it is focused on end-user devices and thus, the equipment of data centers is for example excluded. The selection of these devices is based on products considered in the study of Hilty and Bieser (2017)*. To simplify the analysis, printers and Internet of Things (IoT) nodes analyzed by Hilty and Bieser (2017) are here not included. Concerning the considered fuels, the electricity consumption of the whole Swiss ICT sector (including also the consumption of data centers for example) is considered based on the data from the BFE (2020a, 2020b).

*Hilty and Bieser (2017) analyze greenhouse gas emissions of crucial technologies used within the Swiss ICT sector. Their selection of technologies is used as a reference for the selection of final products within the Swiss ICT sector in the present case study.

The electricity supply for the three considered sectors is broken down into the supply of primary sources including natural gas, coal and uranium. According to the GlobalEconomy.com (2020), almost 50% of the electricity used in Switzerland is domestically produced. Around 30% of this domestic electricity supply stems from nuclear power plants using uranium as a fuel and the remaining 70% is mainly made up by hydroelectricity (Björnsen Gurung et al. 2016). The other half of the electricity used in Switzerland is imported. These imports are assumed to stem from other European countries, where 20% of the electricity is produced from natural gas, 13% from coal, 25% from nuclear and 42% from other sources including mainly renewables (Malerba et al. 2022).

The functional units are defined based on the amounts of fuels or final products listed in Table 9. For the hotspot analysis, the functional unit is specified considering the annual Swiss consumption in the year 2020. It is thus described by the amounts of around 534'000 t of products used in the mobility sector, 36'000 t of products used in the energy generation and storage sector, 26'000 t of products used in the ICT sector and 138 GWh energy-equivalence of fuels. For the impact comparisons, where battery electric cars and conventional cars, solar panels and wind turbines as well as Chinese and German laptops are compared, the functional units are specified based on the same service or number of products related to competing technologies. The functional units are thus described by 100 cars used over 5 years, energy generation technologies producing 6'500'000 kWh of energy (i.e. around 10'000 solar panels or 1 wind turbine according to Allen (2022) and swissenergy (2022)) and 100 laptops. While the impacts of the infrastructure are compared with regard to all considered technologies, the supply of fuels is additionally considered for the comparison between the two car types. Comparing also impacts of fuels is particularly interesting in this case, as different kinds of fuels are needed for electric vehicles and conventional vehicles. The related functional unit is calculated by the average annual driving distance of cars used in Switzerland and the fuel amounts required per km (see the related calculation and data sources in the tab "Comparison BEC and ICEC" in the Excel sheet provided in File 9 in the data repository D.2).

The performance of the hotspot analysis and impact comparisons follows the procedure suggested for the application of the SPOTTER approach explained in section 3.3 (in the following referred to as 'SPOTTER implementation procedure').

Based on step 1 of the 'SPOTTER implementation procedure', supply disruption impacts and events are defined by two impact categories and six events that are relevant for the short-term time horizon. The impacts comprise *cost variability* and *limited availability*. The events include the four country-specific events *geopolitical instability*, *trade barriers*, *child labor restrictions* and *economic resource depletion* as well as the two global events *price volatility* and *limited recyclability of raw materials*. As shown in Figure 21, geopolitical instability, trade barriers and price volatility potentially affect all supply chain processes and are thus analyzed along the full supply chain. Child labor restrictions are in contrast analyzed only at the mineral extraction stage, as it is assumed that child labor may occur during artisanal mining (International Labour Organization 2019) but not during other processes along the supply chains of high-tech products such as the ones included in the present case study. The considered events are described in detail in Appendix A.5 and the impacts are explained in section 3.1.

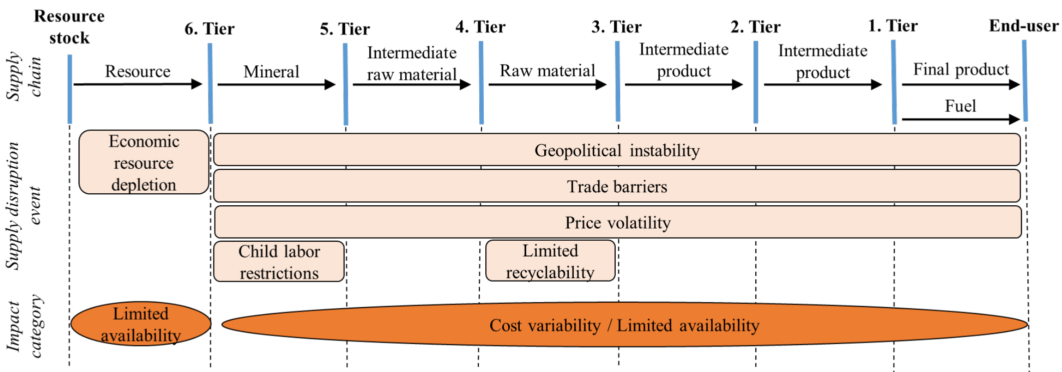

Figure 21: Supply disruption events and impacts considered along the supply chain illustrated based on a generic six-tier supply chain

To assess the considered supply disruption impacts along the supply chains for entire sectors, a rather high amount of inventory flows (i.e. material/product flows between the different country-specific supply chain processes) needs to be analyzed. As already highlighted by Cimprich et al. (2019), such an analysis is related to tremendous efforts regarding data collection and computation. A way to reduce these efforts is to focus on the country-specific material/product flows that are relevant for an assessment of supply disruption impacts across sectors. On that note, inventory flows particularly influential for the assessment with SPOTTER are selected by following the screening procedure described in Figure 22.

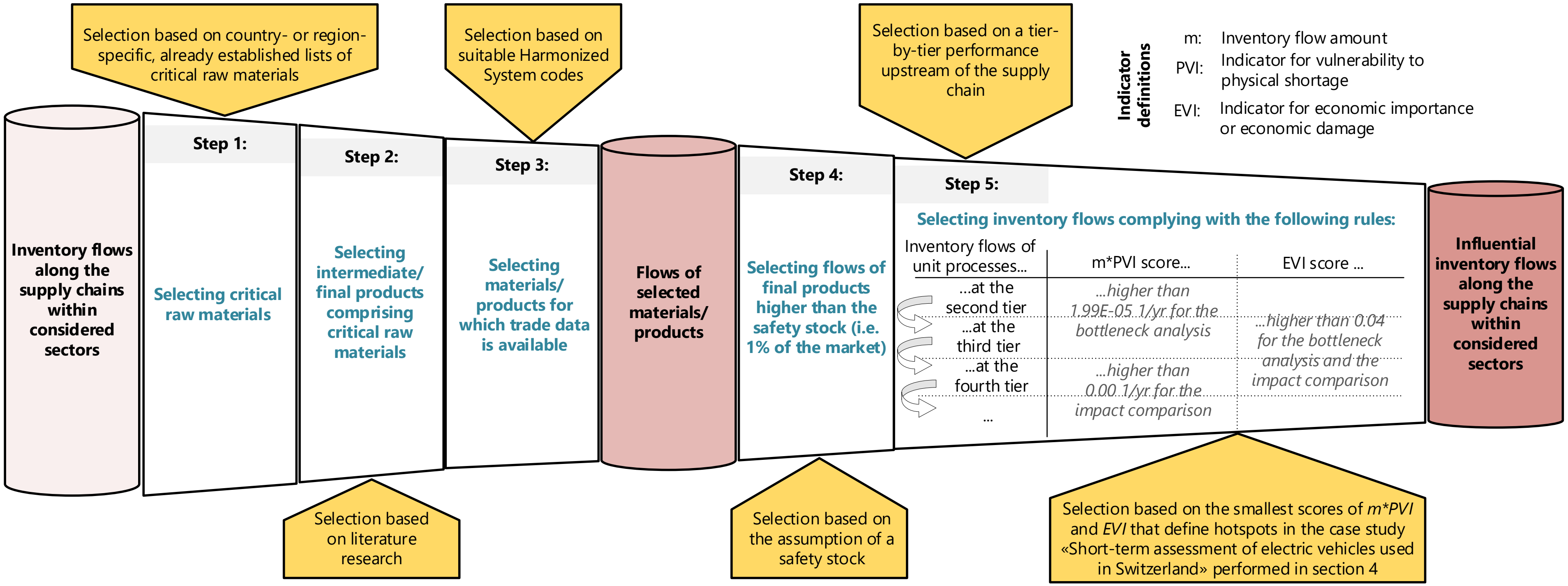

Figure 22: Screening of influential inventory flows
for the analysis of supply disruption hotspots and the performance of impact comparisons with the SPOTTER approach on a sectoral-level. With regard to impact comparisons, no threshold for m*PVI is defined because indicator values to establish such a threshold are currently missing in the literature.

In the first step of this screening procedure, raw materials are identified and selected that are included in lists of critical raw materials for relevant countries or regions. As, for Switzerland, no such lists exist, the 30 raw materials included in the list of critical raw materials for the EU published by the European Commission (2020b) are considered in this case study[12].

In the second step, intermediate and final products are selected that contain these critical raw materials and that are relevant for at least one of the considered sectors, i.e. mobility, energy and/or ICT sectors. For example, LIBs used as traction batteries are selected because they contain the critical raw material *cobalt* (Nature Editorial 2021) and are relevant for the mobility sector (Castelvecchi 2021). The selected intermediate/final products and the literature consulted during the selection process are presented individually for all three considered sectors in the tab "Weight%" of the Excel sheets provided in Files 1 to 3 of the data repository D.2.

In the third step, only those materials and products are selected from the set of materials/products identified after the first two steps, for which trade flows are effectively reported. As demonstrated in sections 4.1.3 and 4.1.4, physical and monetary trade flows are needed for the quantification of the supply chain and the definition of indicators used for the impact assessment. In the present study, BACI (Gaulier and Zignago 2010) is considered as a database to quantify such trade flows. As stated in section 4.1.2, this database is suitable for assessments along the supply chain because it covers physical and monetary trade data for several material/product categories described with 6-digit Harmonized System (HS) codes provided by the World Customs Organization (2021). An example of products selected by following this third step is the LIBs covered by the HS code 850760. Products that however needed to be excluded are nickel-metal hydride batteries used in EVs because the only available HS code related to this battery type (i.e. HS code 850750) is specific to the use of these batteries in mobile phones (World Customs Organization 2021). All the materials/products selected within this third step and the related HS codes are listed in Appendix C.1. In some cases, the content of these HS codes is however too broad to allow for quantifying the flows of the selected materials/products. As explained in section 4.1.2 and illustrated with examples in Appendix B.4, this issue is addressed by using cost-to-mass ratios, which allows for identifying trade data of the specific materials/products. All adjustments related to the content of the HS codes considered in the present case study are explained in File 5 of data repository D.2.

In the fourth step, only flows of final products that are higher than a basic safety stock are selected. This safety stock is determined as 1% of the market (i.e. import and domestic production) following the assumption explained in section 3.3 regarding the definition of safety stocks.

In the fifth step, only the flows of materials/intermediate products that are (i) used in significant amounts and vulnerable to physical shortage as well as (ii) economically important/damaging for the product system are selected. To identify the inventory flows complying with these two criteria, the thresholds

[12] Note that the latest list of critical raw materials for the EU published by the European Commission (2023) has not been available at the time when the present study has been conducted.

presented under step 5 in Figure 22 are used. These thresholds are described by the lowest indicator values that define hotspots in the first case study with SPOTTER *Short-term assessment of electric vehicles used in Switzerland* performed in Chapter 4. Here, the inventory flow amount (m) multiplied by value of the indicator for vulnerability to physical shortage (PVI) as well as the values of the indicator for economic importance or economic damage (EVI) are considered. The *m*PVI* and *EVI* values defining these hotspots are displayed and the values that are consequently identified as the thresholds are highlighted in Appendix C.2.

The most influential inventory flows are then successively selected at each tier of the supply chain starting with the second tier (i.e. manufacturing of intermediate products) and ending with the last tier (i.e. extraction of minerals) by comparing the calculated *m*PVI* and *EVI* values related to each inventory flow against the established thresholds. The calculations of *m*PVI* and *EVI* values are described in detail in the sections 4.1.3 and 4.1.4 and these calculations are outlined in section 5.1.2 and Appendix C.4.

Figure 23 illustrates the selection of influential inventory flows based on the fourth and fifth steps of the screening approach by the example of an extract of the supply chain considered in the hotspot analysis.

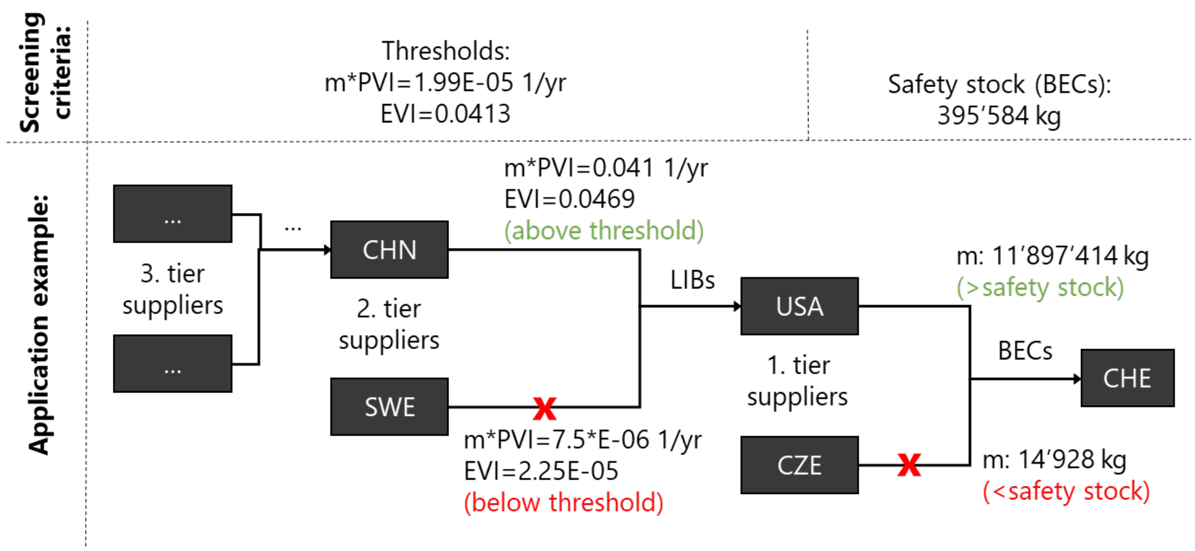

Figure 23: Illustration of the tier-by-tier screening
by the example of an extract of the supply chain representing the supply of lithium-ion batteries (LIBs) for battery electric cars (BECs) used in Switzerland. The thresholds are defined based on the inventory flow amount (m), the values of the indicator for vulnerability to physical shortage (PVI) and the values of the indicator for economic importance or economic damage (EVI). Abbreviations for countries are based on alpha-3 codes.

On the right side of Figure 23, an example for the screening based on the fourth step described in Figure 22 is illustrated. In this example, the flow amount for BECs from the Czech Republic is lower than the safety stock and thus this flow and all connected upstream flows are excluded from the assessment. Conversely, the flow amount for BECs from the United States lies above the safety stock and thus, is included in the assessment. All flows upstream of this and other included final product flows are screened following the fifth step described in Figure 22. As shown on the left side of Figure 23, one of these upstream flows is the flow of traction batteries from Sweden to the United States. Because the associated *m*PVI* and *EVI* values are below the defined thresholds, this flow and all connected upstream flows are excluded from the assessment. Another one of the flows upstream of the BEC supply illustrated in Figure 23 is the flow of traction batteries from China to the United States. Its associated *m*PVI* and *EVI* values lie above the defined thresholds and thus, this flow is included in the assessment.

5.1.2 Inventory analysis

Within the inventory analysis performed based on step 2 of the 'SPOTTER implementation procedure', inventory flows along the supply chain are quantified by following the procedure outlined in Figure 24 and described in detail in section 4.1.3.

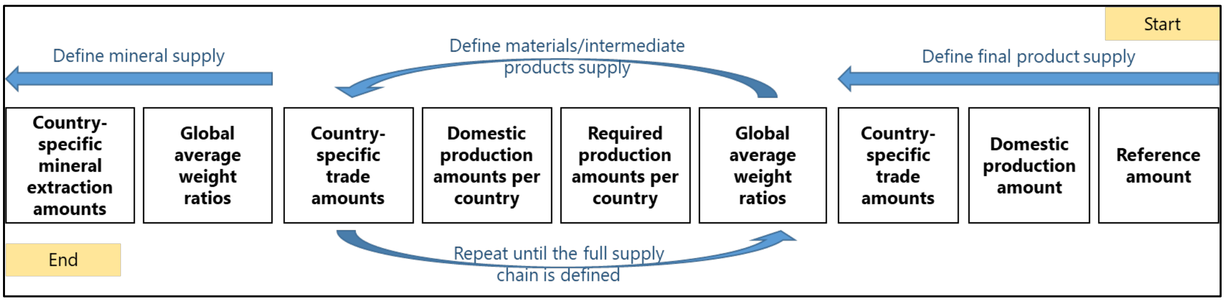

Figure 24: Schematic of the procedure used for modelling the supply chain

First, flows of final products and fuels are quantified (see right part of Figure 24). Here, the reference amount is defined in accordance with the functional unit. Based on this reference amount, the domestic production amounts and the country-specific trade amounts of final products and fuels are determined. Second, the material/intermediate product flows are quantified stepwise upstream of the supply chain (see middle part of Figure 24). This quantification is performed a follows: the afore-defined country-specific trade amounts and respective global average weight ratios are used to define the required country-specific production amounts of the upstream material and then, these production amounts are considered to specify the domestic production and trade amounts of the upstream material per country. This procedure is followed until all material/intermediate product flows are defined. Third, the mineral flows are quantified (see left part of Figure 24) by using global average weight ratios and country-specific mineral production amounts. Details regarding the quantification of the considered supply chains and the used data sources are provided in Appendix C.3.

Simultaneously to the definition of the individual inventory flows, the temporal relevance of the flows over the considered time horizon (i.e. next 5 years) is analyzed in accordance with step 4 of the 'SPOTTER implementation procedure'. The temporal relevance is determined by estimating the number of times the materials/products are supplied over the considered time horizon. The information about product lifetimes, which is used for this estimation, is provided in the tab "data (temporal relevance)" within the Excel sheets provided in Files 6 to 8 of the data repository D.2. A practical example for defining temporal relevance is given in section 4.1.3.

The fourth and fifth steps of the screening procedure described in Figure 22 are executed as an integral part of the inventory analysis, which, at each stage of the supply chain, allows for the identification of the inventory flows that are most influential for the assessment with SPOTTER.

Both, the screening procedure and the inventory analysis (described above) are performed based on python scripts developed within our work.

5.1.3 Impact assessment

Within the impact assessment performed in accordance with step 5 of the 'SPOTTER implementation procedure', the overall impact on the product system is defined by a sum of bottleneck scores as described in Equation (9).

Bottleneck scores, representing the impact scores for individual inventory flows, are calculated by multiplying the inventory flow amounts with respective CFs (see Equation (9)). As shown in Equation (10), the CFs are determined based on values of four basic indicators: (i) *indicator for supply disruption event over a period (EI*t)*, (ii) *indicator for supply diversity (DI)*, (iii) *indicator for vulnerability to physical shortage (PVI)* and (iv) *indicator for economic importance/damage (EVI)*. To aggregate the individual bottleneck scores into the impact categories *cost variability* and *limited availability*, the *EI* and *DI* values are summarized into *indicator for probability of supply disruption (PI)* values, which are then consistently scaled following Equation (19). The specific definitions of all indicators are explained in section 3.2.3 and the quantification of the indicators is described in detail in section 4.1.4 and outlined in Appendix C.4. The indicator values and impact scores used in the present case study are calculated based on python scripts developed within our work.

5.1.4 Interpretation

The impact scores calculated during the impact assessment presented in section 5.1.3 are the basis for the hotspot analysis and the impact comparison. Supply disruption hotspots are identified per impact category on the level of the Swiss economy (i.e. a combination of the Swiss mobility, energy and ICT sectors) and on the level of each of the three sectors individually. As explained in section 4.1.5, these hotspots are defined by considering all impact scores that are higher than 1% of the overall impact per impact category. Regarding the impact comparison, overall impact scores are compared between (exemplary) competing technologies within each of the three considered sectors (i.e. between battery electric cars and conventional cars, between wind turbines and solar panels as well as between Chinese laptops and German laptops).

5.2 Results and discussion

5.2.1 Flows of considered materials/products and fuels

Figure 25 shows material/product flows described in physical units (i.e. in tons) across the Swiss mobility, energy and ICT sectors that have been selected after the third step of the screening procedure described in Figure 22. To simplify the visualization, the mineral and (intermediate) raw material flows are presented by their pure metal content. The actual weight of these minerals and (intermediate) raw materials can be calculated based on the metal contents described in Table C4. There is no mass balance along the visualized supply chains because certain flows of materials/products have not been selected for the impact assessment with the SPOTTER approach during the screening procedure. For example, all iron and copper flows have been excluded as these two metals are not rated as critical by the European Commission (2020b). To provide a more specific view of the mobility, energy and ICT sectors, material/product flows are illustrated individually for each of the sectors in the Figures C1, C2 and C3 shown in Appendix C.5.

Figure 26 shows the considered fuel supply across the Swiss mobility, energy and ICT sectors. As explained in section 5.1.1, the electricity supply is broken down into its primary sources including natural gas, coal and uranium.

The amounts of the selected material/product and fuel flows illustrated in Figure 25 and Figure 26 are reported in the tabs "Infrastructure" and "Fuel" of the Excel sheet provided in File 4 of the data repository D.2.

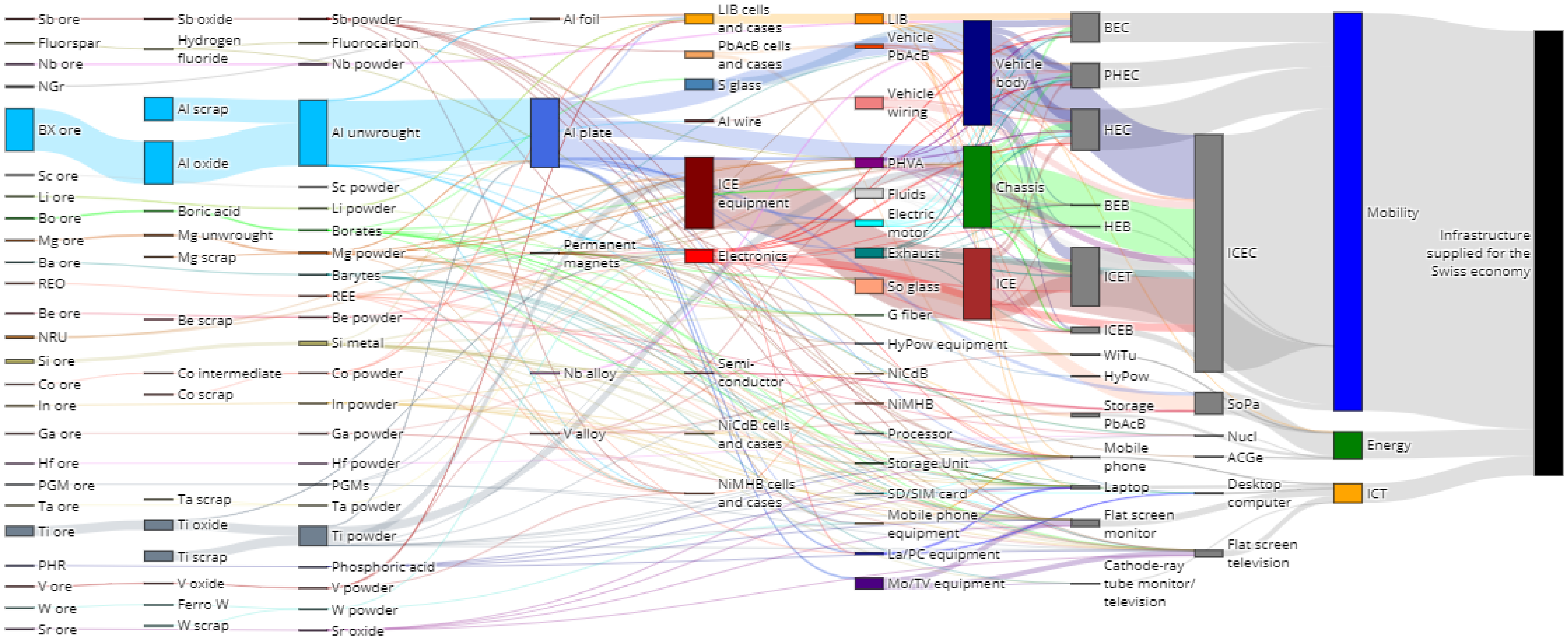

Figure 25: Flowchart of considered materials/products
(consisting of around 534'000 t mobility equipment, 36'000 t energy provision and storage equipment and 26'000 t ICT equipment) used in the Swiss mobility, energy and ICT sectors in the year 2020. The following abbreviations are used for the materials/products: BEC: Battery electric car, PHEC: plug-in hybrid electric car, HEC: Hybrid electric car, ICEC: Internal combustion engine car, BEB: Battery electric bus, HEB: Hybrid electric bus, ICEB: Internal combustion engine bus, ICET: Internal combustion engine truck, SoPa: Solar panel, WiTu: Wind turbines, HyPow: Hydropower plant, PbAcB: Lead-acid battery, Nucl: Nuclear power plant equipment, ACGe: AC Generators, LIB: Lithium-ion battery, ICE: Internal combustion engine, PHVA: Instrumental panel, heating, ventilation and air conditioning, So_glass: Solar glass, G_fiber: Glass fiber, NiCdB: Nickel-cadmium battery, NiMHB: Nickel-metal hydride battery, La/PC_equipment: Equipment for laptops/desktop computers, Mo/TV_equipment: Equipment for monitors/televisions, Sb: Antimony, Al: Aluminium, Ba: Barium, Be: Beryllium, Bo: Boron, Co: Cobalt, Ga: Gallium, Hf: Hafnium, In: Indium, Li: Lithium, Mg: Magnesium, Nb: Niobium, NGr: Natural graphite, NRU: Natural rubber, PGM: Platinum Group Metal: PHR: Phosphate rock, REE: Rare Earth Elements, REO: Rare Earth Oxides, Sc: Scandium, Si: Silicon, Sr: Strontium, Ta: Tantalum, Ti: Titanium, V: Vanadium, W: Tungsten

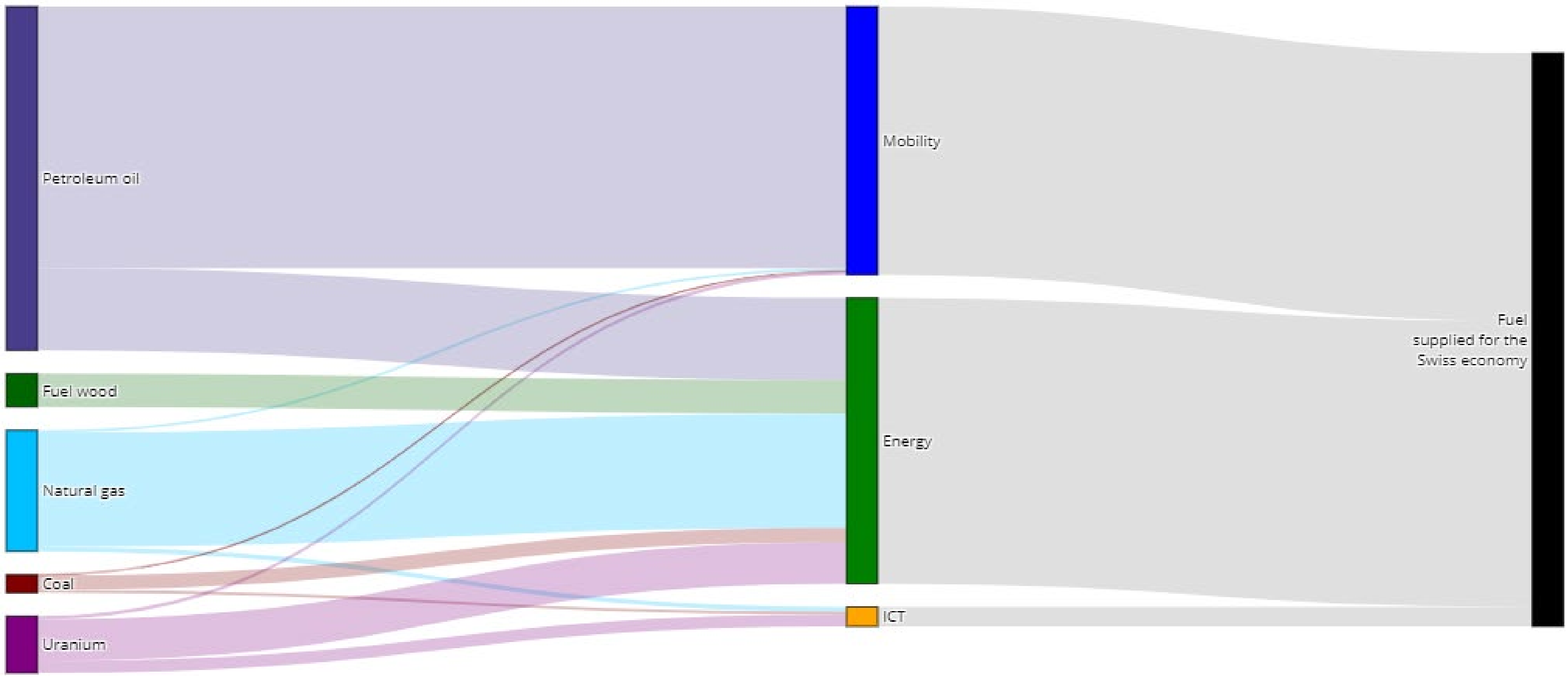

Figure 26: Flowchart of considered fuels
(consisting of fuels equivalent to around 64.58 GWh for mobility, 68.79 GWh for energy provision and storage and 4.68 GWh for ICT) used in the Swiss mobility, energy and ICT sectors in the year 2020

Concerning the flows of materials/products illustrated in Figure 25, the following four observations can be made:

First, several critical raw materials (i.e. 25 out of the 30 raw materials included on the list of critical raw materials published by the European Commission (2020b)) are utilized within the Swiss mobility, energy and ICT sectors. As also shown by Zepf et al. (2014), the high-tech technologies such as electric vehicles, solar panels and smartphones used within these three sectors thus consume a variety of critical raw materials.

Second, a comparison of the Swiss supply amounts of the three here investigated sectors shows that the largest amounts of materials/products are supplied to Switzerland in form of transportation equipment. The differences in supply amounts can be explained by the higher number of used items and shorter lifetime of consumer goods such as vehicles and electronic devices compared to the considered energy generation infrastructure as well as by the higher weight of vehicles compared to the considered electronic devices.

Third, the largest supply amounts of critical raw materials are associated with the flows of aluminium and titanium. These two metals are often a major part of structural components, which commonly have a high contribution to the overall product mass. For example, aluminium is a major constituent of vehicle bodies (Demirkesen and Uçar 2020) and titanium is a commonly-used component of the chassis and the exhaust system (AMT 2014).

Fourth, there are several competing applications of critical raw materials between the three sectors, as most of these raw materials are used in a variety of products and components. One example of such competing applications is the use of magnesium, which is an important material for the production of vehicles (Kiani et al. 2014), wind turbines (Chawla 2001; Liu and Barlow 2016) and flat screens (De La Torre et al. 2018). Another example is the use of cobalt, which is a crucial element of batteries and magnets included in products of the mobility, energy and ICT sectors (BJMT/Ideal 2014; Nature Editorial 2021).

Concerning the flows of fuels illustrated in Figure 26, it is shown that the highest amounts of fuels are used for the energy and mobility sectors and that the main Swiss energy sources are petroleum oil followed by natural gas and uranium.

5.2.2 Hotspot analysis for the Swiss economy

Figure 27 and Figure 29 display – for the here investigated sectors – world maps illustrating the geographical locations of potential supply disruption hotspots along the global supply chains of the Swiss economy. These hotspots represent impacts higher than 1% of the overall impact scores for cost variability and/or limited availability. The arrows on the world maps indicate the locations of the supply disruption hotspots. Solid arrows refer to hotspots stemming from country-specific events. They range from the country, where the supply disruption event occurs to the country affected. Dashed arrows ranging from the top or the bottom of the map represent global events affecting a specific country. Red crosses denote the locations of supply disruption events and the sizes of circles placed on top of affected countries indicate the magnitude of respective impacts.

Figure 27a and Figure 27b represent hotspots related to cost variability and limited availability of materials/products and Figure 27c displays hotspots related to potential supply disruption impacts of fuels. An equal impact related to the cost variability and limited availability of fuels is estimated because, following the explanations of eia (2021) regarding the supply and demand dynamics of natural gas, it is assumed that reduced supply of fuels inevitably leads to higher costs. Furthermore, the impacts of materials/products and the impacts of fuels are presented separately as related impact scores are not comparable due to differences in the types of analyzed flows (i.e. analysis of energy flows in the case of fuels and mass flows in the case of materials/products).

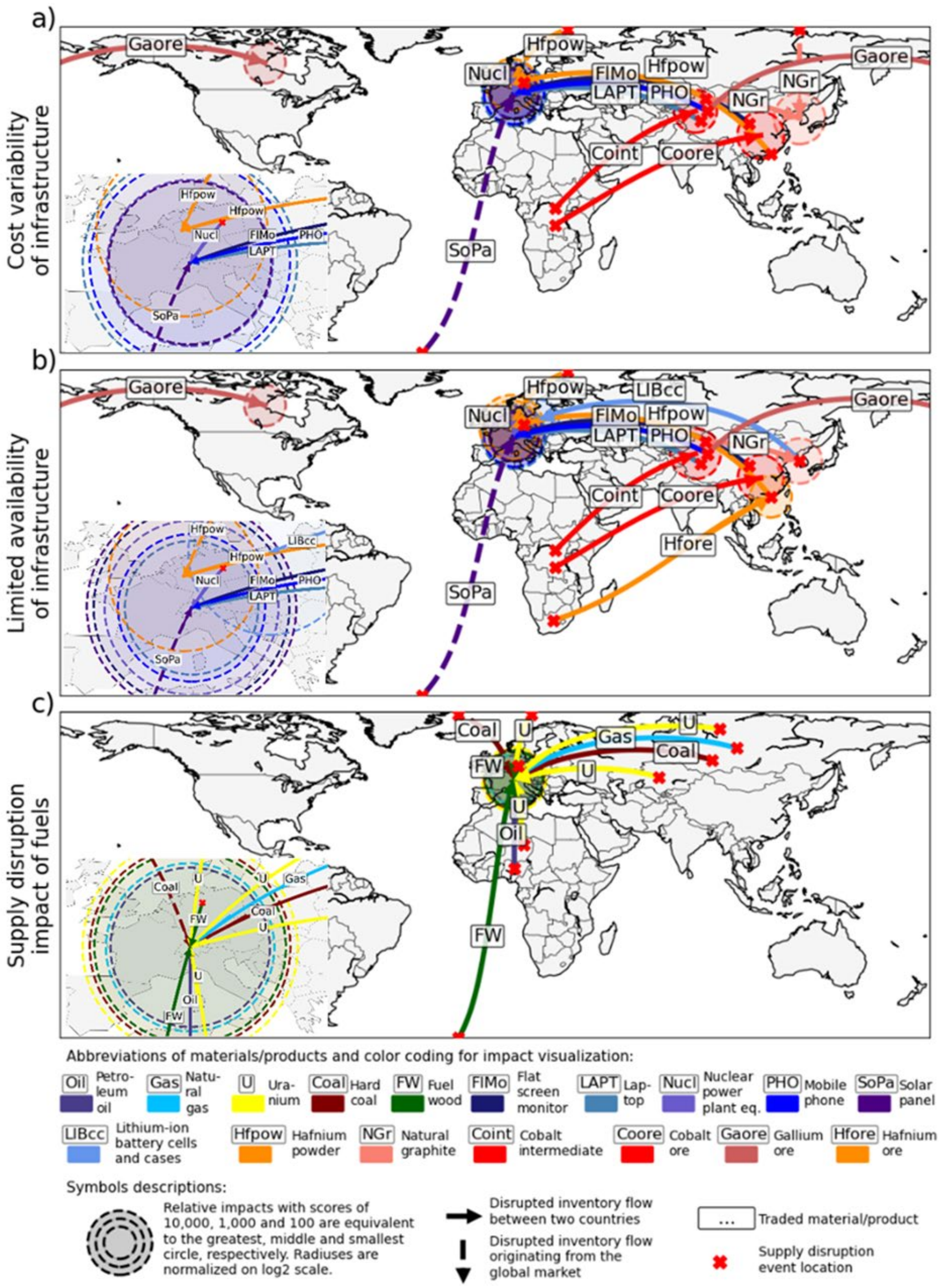

Figure 27: Supply disruption hotspots for the Swiss economy
represented by a) cost variability and b) limited availability of materials/products as well as c) potential supply disruption impact of fuels along the supply chains within the Swiss mobility, energy and ICT sectors. For the reason of clarity, hotspots of materials/products are visualized with red/brown color shades for upstream supply chain stages and with blue/purple color shades for downstream supply chain stages. For better visualization, an extract of Europe is shown in the left corner of the maps.

The majority of hotspots presented in Figure 27a and Figure 27b (i.e. 11 out of 14 hotspots) are hotspots of both, cost variability and limited availability. Two examples are impacts of laptops supplied from China to Switzerland and impacts of gallium ore supplied from China to Canada. Thus, the indicated potential supply disruptions could be related to a price hike or a physical unavailability. The reason that impacts cannot clearly be assigned to cost variability or limited availability is, as explained in section 4.2.1, the missing knowledge regarding effect sizes that would provide a better understanding of whether the impacts refer to price hikes or physical unavailability.

Overall, 14 hotspots related to material/product flows (see Figure 27a and b) as well as ten hotspots related to fuel supply (see Figure 27c) have been identified. The contributions of these hotspots to the overall impact are illustrated in Appendix C.6 with stacked bar charts. Figure 28 presents these contributions, for illustration purposes, on the level of the individual materials/products and fuels.

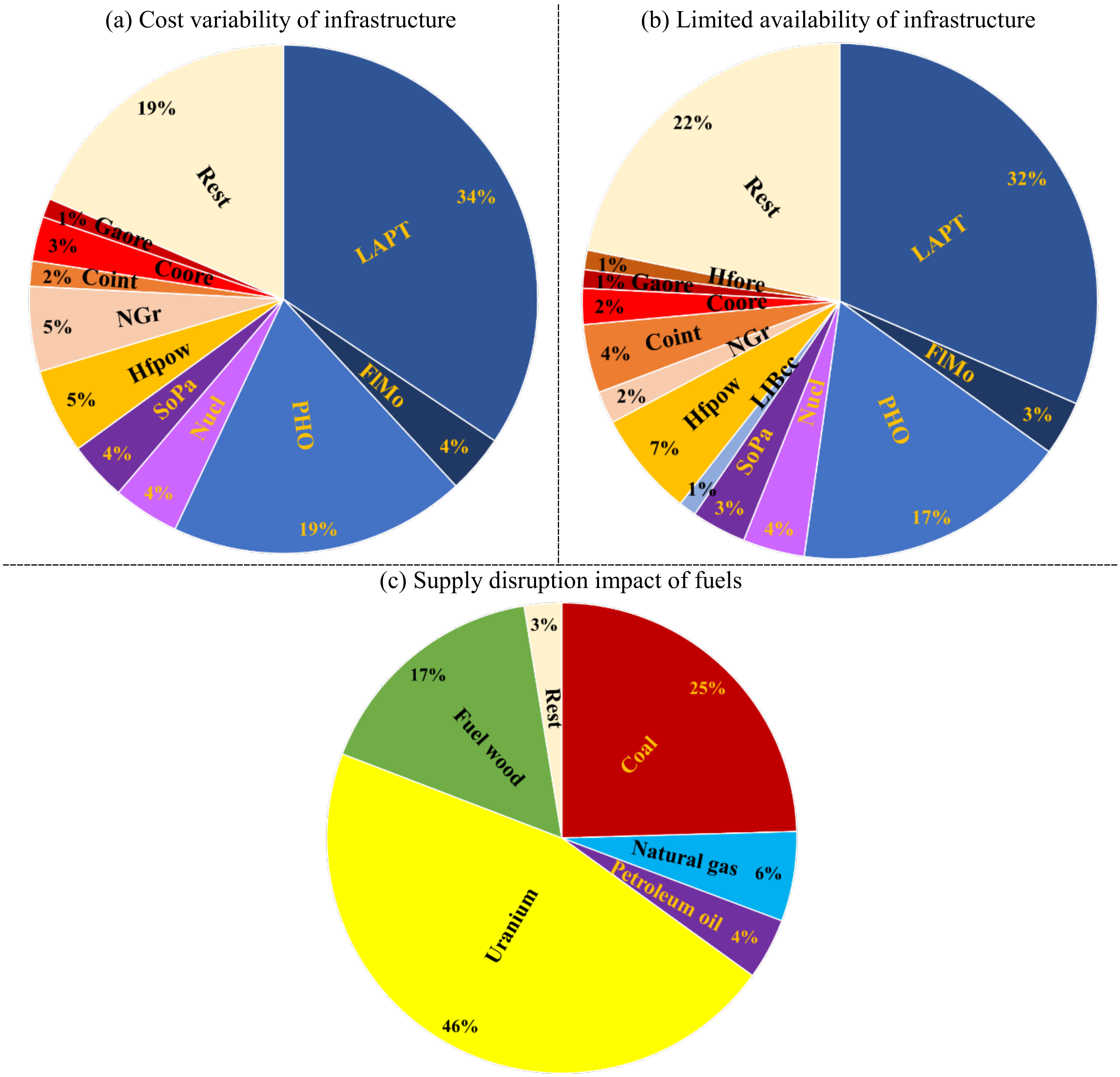

Figure 28: Magnitude of supply disruption hotspots for the Swiss economy considering (a) cost variability and (b) limited availability of infrastructure as well as (c) supply disruption impact of fuels. Abbreviations for the materials/products are explained in Figure 27.

Concerning the hotspots related to material/product flows, four groups of relevant impacts are identified. The first group covers the impacts of electronic devices such as flat screen monitors, mobile phones or laptops traded from China to Switzerland. These impacts mainly stem from two factors. One is the high supply concentration in China, as, according to Robertson and Riley (2018), 75% of the world's mobile phones and 90% of the globally used personal computers are produced in this country. The other factor is the lack of domestic production and the thus-resulting high economic importance of Chinese electronic devices for Switzerland. Following Eichenauer (2021), China is not only one of the most important trade partners for Switzerland but also telecommunication devices and computers constitute, with a value of several billion Euros, the trades of the highest value from China to Europe.

The second group includes the impacts caused by potential disruptions of solar panel supply. On the one hand, there is a high likelihood of supply disruption due to volatile prices because, as explained by Purtill (2023), the recent drop in their prices may be followed by a period of fluctuating prices in the future. On the other hand, the vulnerability to physical shortage is particularly high for solar panels. Their physical shortages cannot easily be mitigated by the supply of materials from EoL products because the amount of solar panels reaching end-of-life is low compared to their production amounts (see the annual production statistics over time described by BloombergNEF (2022b)) and the recycling system for this technology is yet unestablished (Crownhart 2021).

The third group comprises impacts caused by potential supply disruptions of materials and components relevant to various applications within the Swiss economy. Cobalt, natural graphite and battery cells are important constituents of permanent magnets or LIBs applied within the mobility, energy storage and ICT sectors (BJMT/Ideal 2014; Nature Editorial 2021; Pagliaro and Meneguzzo 2019; Vermont 2020). Gallium is used in flat screens of monitors and televisions as well as in semiconductors of solar panels (Buchert et al. 2012; Frischknecht et al. 2020). The several application areas of these materials/products inevitably indicate their particular importance for the economy and thus their comparably high potential supply disruption impacts. Besides the economic importance of these materials/components, they are often associated with high probabilities of supply disruption. In case of cobalt, the supply from Congo is likely to be disrupted because its primary production is highly concentrated in Congo, a country where high risks of geopolitical instability, trade barriers and child labor restrictions exist (Benoit Norris et al. 2019; World Bank 2019, 2020). In case of gallium, natural graphite and battery cells, high likelihoods of supply disruption mainly stem from the supply concentration of these materials/products in China (Idoine et al. 2022; Mayyas et al. 2019).

The fourth group covers impacts caused by potential supply disruptions of nuclear power plant equipment (including fuel elements and nuclear control rods) and the hafnium used in this equipment. A reason for these hotspots is the high dependency of Switzerland on the supply of nuclear fuel elements and control rods, as around one third of the electricity used in Switzerland is generated by nuclear power plants (Björnsen Gurung et al. 2016). Reasons specifically for potential supply disruptions of hafnium are large hafnium trading costs due to high prices (i.e. price of almost 1000$/kg for the pure metal according to USGS (2022f)), concentrated hafnium supply in Hong Kong and hafnium ore supply in South Africa according to BACI and Idoine et al. (2022)[13] as well as high risk of price volatilities for hafnium (Judge 2023).

Concerning the hotspots related to fuel supply, two types of relevant impacts are identified. One is the impacts of natural gas, uranium and coal supplied from Russia as well as uranium and petroleum oil supplied from Niger and Nigeria. These impacts stem mainly from supply concentrations on countries associated with high risks of geopolitical instabilities and trade barriers as well as the high dependency of the Swiss economy on fossil fuels. The other type is the impacts of coal, uranium and fuel wood originating from the global market. The reasons are the relatively concentrated extraction of these fuels in a few countries and their potential price volatilities, which have also been reported by IEA (2022), Salmonsen (2022) and Morgan (2022).

5.2.3 Hotspot analysis for the Swiss mobility, energy and ICT sectors

To illustrate the supply risks per sector, Figure 29 displays hotspots of cost variability (i.e. Figure 29a, c and e) and limited availability (i.e. Figure 29b, d and f) of materials/products for the Swiss mobility, energy and ICT sectors. Besides hotspots already presented for the Swiss economy in Figure 27, additional sector-specific hotspots are illustrated. For example, impacts of lithium supplied from Chile to China are presented specifically for the mobility and ICT sectors (see Figure 29a, b, e and f) and impacts of solar panels imported from China are identified specifically for the energy sector (see Figure 29c and d).

Overall, most of the hotspots identified in Figure 29 refer to intermediate/final products traded from Asia to Europe or materials supplied by African or Asian countries.

[13] According to USGS (2022e), hafnium is produced as a by-product of zirconium in a ratio of 1 to 36. In the present study, the supply concentration of hafnium is thus estimated based on the country-specific supply distribution of zirconium.

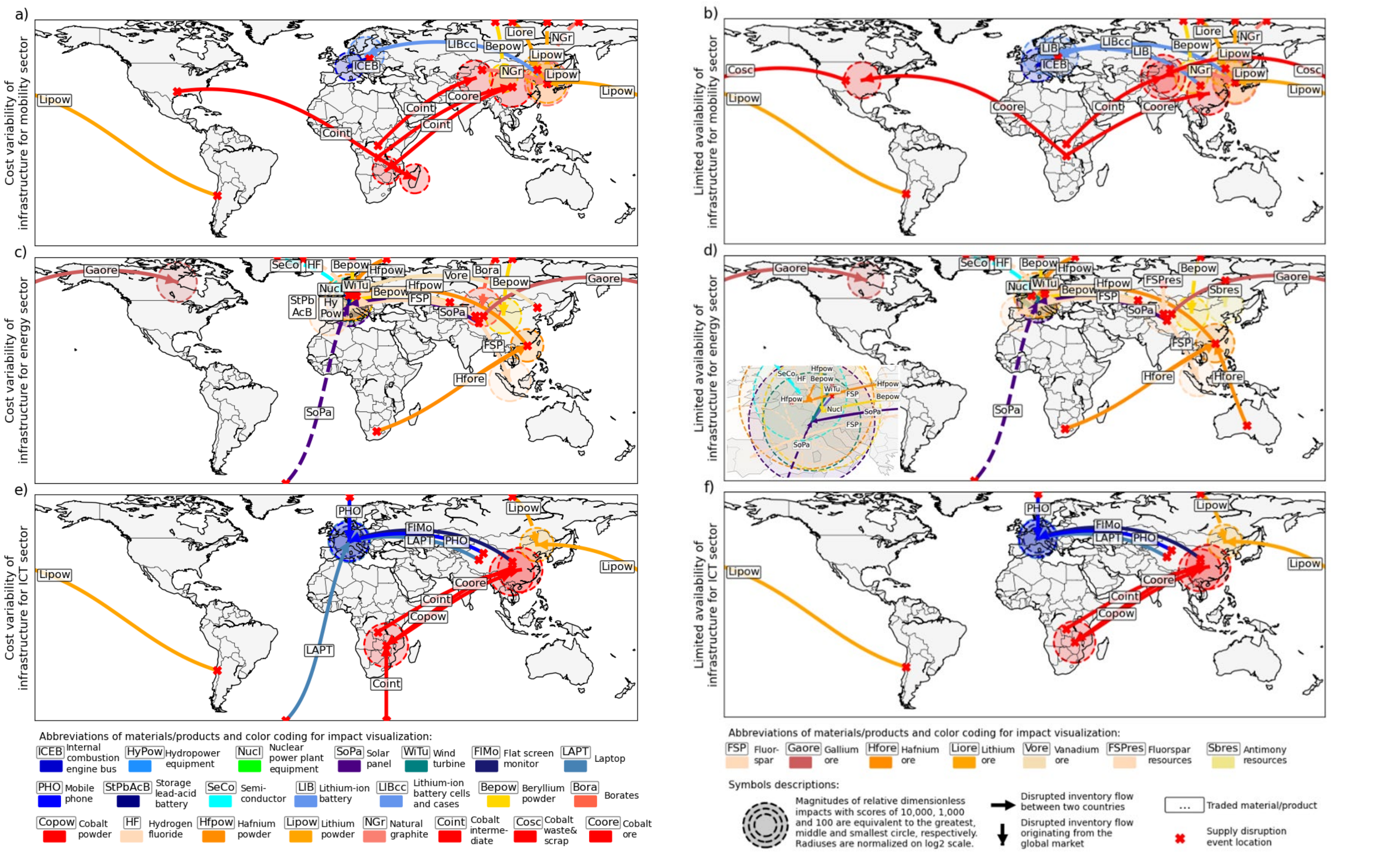

Figure 29: Supply disruption hotspots for the Swiss mobility, energy and ICT sectors

In the mobility sector (Figure 29a and b), the hotspots are mainly related to the flows along the supply chain of traction batteries including the supply of the batteries themselves or their cells as well as flows along the cobalt, lithium and natural graphite value chain. The vulnerability to physical shortages of these materials/components is comparably high, which is due to relatively large production amounts in relation to in-use stocks. Flows of electric vehicles themselves are not identified as hotspots even though electric vehicles are an emerging technology with relatively large production amounts compared to in-use stocks. These flows do not appear as hotspots because the high amounts of conventional vehicles that are currently on the market and in use are assumed to allow for compensating potential supply disruptions of electric vehicles over the next five years. Such compensation is possible through a longer utilization of already-used vehicles but less and less through the purchase of a new conventional car because, as already explained in section 4.2.2, following the Clean Vehicles Directive implemented by the European Parliament and Council (2019), it is aimed to gradually phase out the sales of conventional vehicles by 2035.

In the energy sector (Figure 29c and d), several hotspots are identified related to flows of materials/components used in solar panels, which, as shown in Figure 25, have a relatively high level of utilization in Switzerland compared to other energy generation technologies. These materials/components are semiconductors, gallium, beryllium, borates and vanadium. Other hotspots illustrate the reliance of the Swiss economy on the supply of solar panels, wind turbines, lead-acid batteries as well as hydropower and nuclear power plant equipment. A last category of hotspots suggests a high criticality of fluorspar/hydrogen fluorides and hafnium, which are, as explained in section 5.2.2, of economic value for nuclear power technologies.

In the ICT sector (Figure 29e and f), the identified hotspots indicate the dependency of Switzerland on imports of electronic end-user devices including laptops, mobile phones and flat-screen monitors from China as well as suggest relatively high criticalities related to flows of cobalt and lithium used in the permanent magnets or batteries of such devices.

5.2.4 Technology comparisons

In Figure 30, the overall cost variability is compared between battery electric cars (BECs) and internal combustion engine cars (ICECs), between solar panels and wind turbines as well as between Chinese laptops and German laptops. All of these technologies are, as explained in section 5.1.1, relevant technologies within the mobility, energy and ICT sectors.

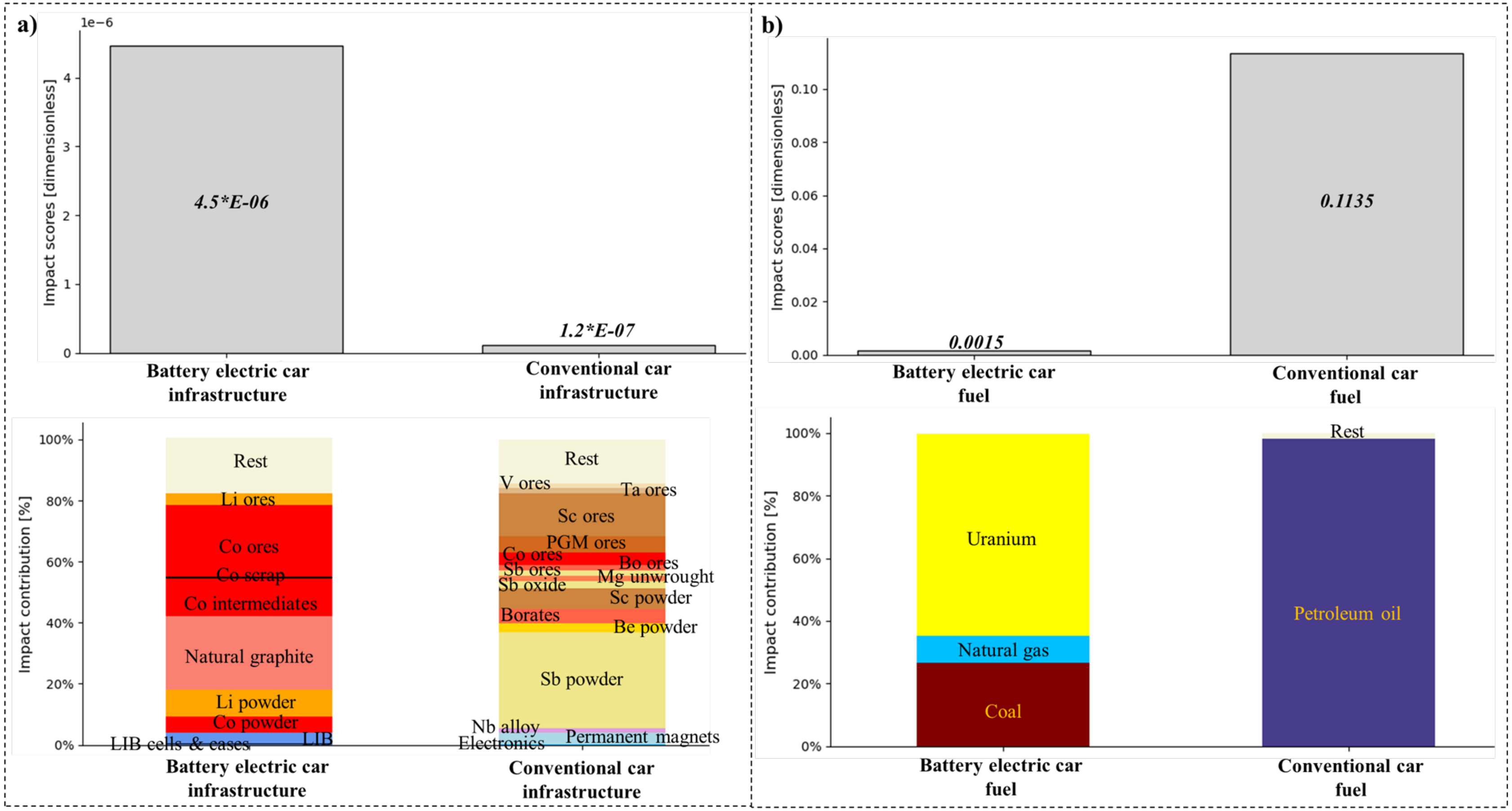

Figure 30: Comparison of overall cost variability between key technologies
considering a) the infrastructure and b) the fuels of battery electric cars and conventional cars, c) the infrastructure of solar panels and wind turbines as well as d) the infrastructure of Chinese and German laptops. The upper bar charts present overall impacts and the lower bar charts show impact contributions of materials/products. The used material/product abbreviations are explained in Figure 25.

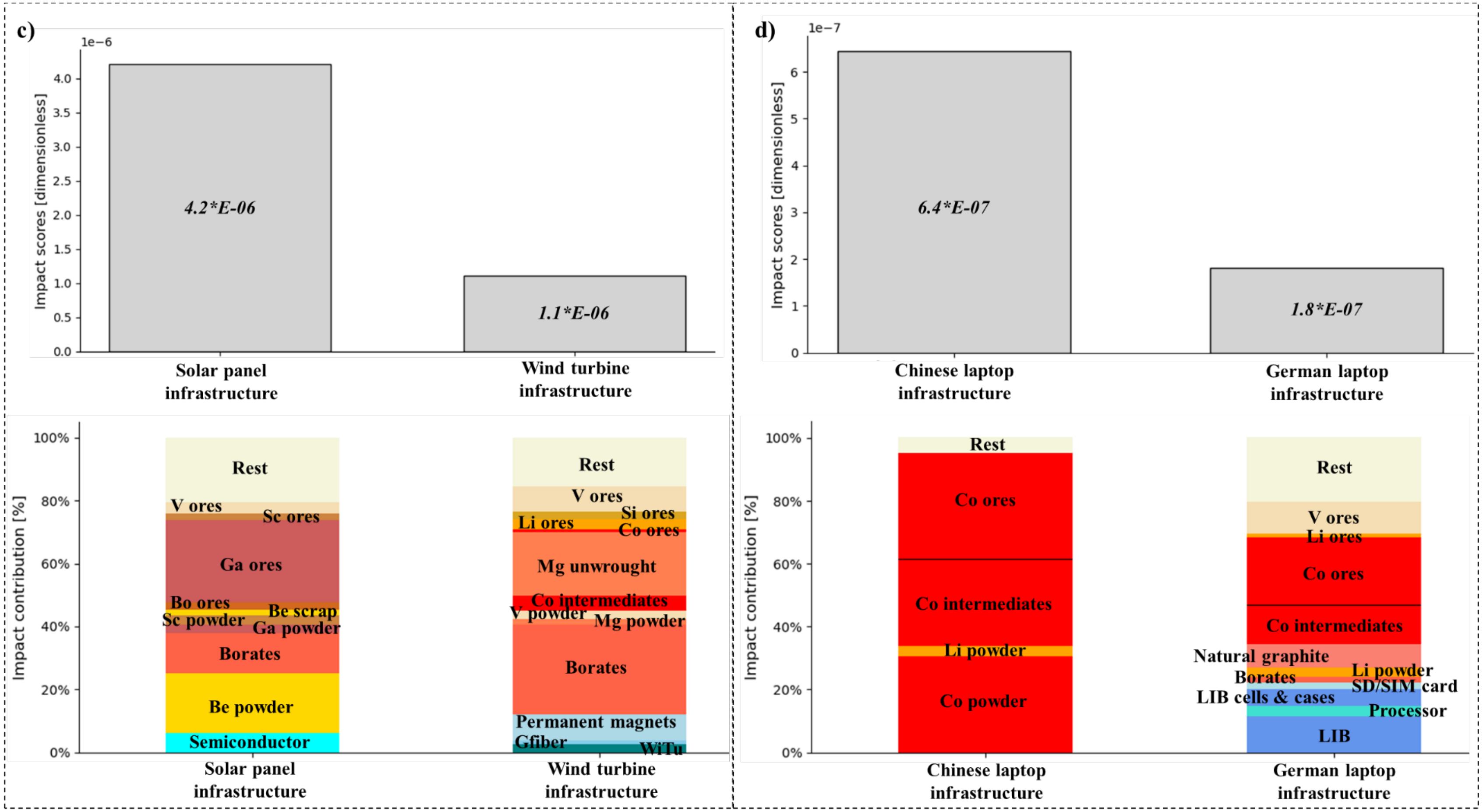

Figure 30 (continued)

The upper part of Figure 30a shows that the cost variability is more than 35 times higher for the infrastructure of BECs than for the infrastructure of ICECs. Overall, rather material flows than product flows contribute to the impacts for the two car types (see lower part of Figure 30a). The main contributors to the impact for BECs are flows of cobalt, lithium, natural graphite and battery cells. These flows have also been identified as hotspots for the Swiss mobility sector in Figure 29a. The impact for ICECs stems from a variety of material/product flows. The ones with the comparably highest contributions are the flows along the value chains of antimony and platinum group metals (PGMs) used in car electronics or catalysts and flows along the value chain of scandium included in structural components.

Conversely, regarding fuel supply the cost variability is more than 75 times higher for the petroleum oil used in ICECs than for the supply of electricity used to drive BECs (upper part of Figure 30b). The reasons are mainly the higher amounts of fuel (measured in energy-equivalency) needed for driving ICECs[14] and the domestic electricity supply from renewable energy sources such as solar and wind power, which is here considered risk-free. As shown in the lower part of Figure 30b, the main contributors to the impact on fuel supply for BECs are flows of uranium, coal and natural gas.

Concerning the comparison between solar panels and wind turbines, cost variability may occur for the installation of both technologies. Nevertheless, as shown in the upper part of Figure 30c, the cost variability for solar panels is identified as almost four times higher than for wind turbines. A reason is supposedly that the generation of the same amount of energy requires a higher number of critical raw materials (i.e. 11 in solar panels and 8 in wind turbines) and larger amounts of components comprising critical raw materials[15]. The lower part of Figure 30c shows that the main contributors to the impact for solar panels are flows of semiconductors as well as flows of beryllium, borates, gallium, scandium and vanadium mainly used in semiconductors or solar glass. The main contributors to the impact for wind turbines are in turn flows of borates, magnesium, lithium and silicon used in glass fibers, flows of cobalt used in generator magnets and vanadium used in the rotor as well as flows of glass fibers, permanent magnets and the wind turbine itself.

The upper part of Figure 30d suggests an around three times higher cost variability for Chinese laptops compared to German laptops. The reason for the differences in these impacts is supposedly the less diversified cobalt supply chain of the laptops imported from

[14] The energy consumed per distance is 0.96 kWh/km for ICECs and 0.20 kWh/km for BECs, following the information about energy expenditure provided by Mamala et al. (2021).

[15] It is estimated that an amount of around 220 t of solar panels and 37.6 t of rotor, engine and generator used in wind turbines generate the same amount of energy. The related calculations and data sources are explained in the tab "data_1tier" in the Excel sheet provided in File 7 of the data repository D.2.

China. Indeed, the supply chain modeled for these laptops indicates a high dependency on cobalt powder from Zambia, cobalt intermediates from China and cobalt ores from Congo. As already shown in Figure 27, these trades are evaluated as particularly unstable due to high risks of geopolitical instabilities, trade barriers and child labor restrictions. The main contributors to the impact for German laptops are flows of LIBs, processors, lithium powder, natural graphite, cobalt intermediates, cobalt ores and vanadium ores mainly traded from China to Germany (see lower part of Figure 30d).

5.2.5 Comparison with existing studies

LCSA studies conducted by Bach et al. (2017b) and Arendt et al. (2020) have already assessed supply disruption hotspots on the level of the German and European economies. Their studies confirm the high impacts of petroleum oil, gallium, cobalt and beryllium identified in our study. However, their studies do not indicate the hotspots of mineral or intermediate/final product supply that are also presented in our study, as only impacts at the raw material production stage but not at other supply chain stages have been analyzed there.

The EU Foresight Study developed by Carrara et al. (2023) provides a criticality assessment for the EU that considers different stages of the supply chains. Their assessment is however performed outside of the LCSA framework and thus inevitably misses the benefits of integration into this framework described in section 1.3. In accordance with our study, the EU Foresight Study highlights for example the European dependency on the supply of solar panels, mobile phones, laptops and LIBs from China as well as reports a high criticality for cobalt, lithium, natural graphite, gallium and borates used in LIBs or solar panels. However, some of the hotspots identified in our study have not been shown in the EU Foresight Study. One example is the impacts related to the cobalt ore flow from Congo to China. This flow, which constitutes a particularly large flow along cobalt supply chains according to Sun et al. (2019), could not be considered by the EU Foresight Study because this study analyzes only direct imports to the EU. Another example is the impacts caused by the price volatility of solar panels, which could not be assessed with the EU Foresight Study, as this study is limited to the analysis of geopolitical instability. A third example is the hotspots identified for petroleum oil or natural gas. These hotspots are disregarded in the EU Foresight Study, as an analysis of fuels is not included in this study.

LCSA studies performed by Cimprich et al. (2017, 2018) and Sun et al. (2021) have analyzed supply disruption hotspots of raw materials used in BECs and ICECs as well as compared the impacts of both car types. By assessing impacts caused by events such as geopolitical instability, trade barriers, price volatility and/or limited recyclability, the authors have evaluated impacts that are similar to the ones assessed in our study. In accordance with our study, those authors show higher impacts for most of the materials used in BECs and a higher overall impact for BECs in comparison to conventional cars. Sun et al. (2021) identify, similar to our study, cobalt, lithium and natural graphite as the main contributors to the impacts as well as hotspots related to the supply of various materials used in electronics such as antimony, beryllium, gold, PGMs and tantalum. However, the identification of hotspots also varies among the three studies. For example, impacts of cobalt, neodymium, magnesium, gold and antimony are identified as hotspots in one or two studies but not in all three studies. One reason for these variations in the identified hotspots is the different material selections. For example, antimony, cobalt, lithium and gold are not included in the bill of materials in all three studies. Another reason is the different scopes of the three studies. The supply chains are analyzed from a Chinese (Sun et al. 2021), a European (Cimprich et al. 2017, 2018) and a Swiss perspective (our study). The supply of vanadium and antimony is for example rated as critical from a Swiss perspective but not from a Chinese perspective, as the two metals are produced in China but not in Switzerland according to the British Geological Survey (Idoine et al. 2022). Another difference is that our study, in contrast to the studies of Sun et al. (2021) and Cimprich et al. (2017, 2018) is not limited to the supply of raw materials but considers the material/product trade flows along the supply chain.

Overall, our study, in comparison to existing studies, provides new information about supply risks on the level of the country-specific trade partners and the different supply chain stages. The additional knowledge about the risks along the supply chains that can be gained with this information could help to identify suitable mitigation measures.

5.2.6 Possible risk mitigation measures

This section suggests possibilities for mitigating supply risks indicated by the four hotspot groups presented in section 5.2.2. As risks have been assessed for country-level supply chains of Switzerland over the next five years, our suggestions are particularly targeted towards the designers of the Swiss resource strategy for this time horizon as well as towards Swiss companies and retailers. The list of generic risk mitigation measures presented in the report of Spörri et al. (2017) has been used as support for the identification of the suggested measures.

The first group of material/product hotspots and fuel hotspots refers to the dependency on imports of laptops, mobile phones and flat screen monitors from China as well as the reliance on natural gas, uranium and petroleum oil supply from Russia, Niger and Nigeria. One possibility to decrease these dependencies would be diversification and restructuring of supply chains by importing these products and fuels from other, possibly more reliable suppliers. Another possibility to mitigate particularly the supply risk related to fuels is a shift from fossil fuel infrastructures towards infrastructures based on electricity. As shown in Figure 30b by the example of transport technologies, this would result in decreasing supply disruption impacts.

The second group of material/product hotspots and fuel hotspots describes potential supply disruptions due to price volatilities of solar panels, coal, uranium and fuel wood. These risks could be mitigated by adopting hedging strategies.

The third group of material/product hotspots covers the impacts of materials/products that are crucial for the production of key technologies. Examples are cobalt, lithium, natural graphite, gallium, beryllium, borates, magnesium, battery cells, semiconductors and permanent magnets used to produce LIBs, solar panels or wind turbines. To mitigate the supply risk for these critical materials and intermediate products, as already suggested in section 4.2.5 for the example of risks related to traction battery supply, policy-makers could provide funding for research activities and support the construction of infrastructure related to an establishment of a circular economy for Switzerland. Conversely, the possibilities of Swiss companies and retailers are limited regarding the implementation of measures to mitigate these supply risks. The reasons are the widely missing domestic production of end-products used in the mobility, energy and ICT sectors in Switzerland and the thus low influence of the Swiss economy on the global market related to these three sectors. However, producers of final products in other countries could conclude long-term contracts with possibly more reliable suppliers of raw materials and intermediate products, identifying these suppliers for example by using the list of national reputation ratings published by Knoema (2022). Furthermore, countries, where the relevant producers of final products are located, could build up stockpiles comprising the most critical raw materials. Comparing the impact scores presented in Figure 30d and Figure 31, creating for example stockpiles of cobalt in China and Germany to mitigate the risk of cobalt supply would supposedly lead to lower overall supply disruption impacts of German and Chinese laptops. Especially, the overall impact of Chinese laptops would decrease resulting in a magnitude lower than the impact magnitude of German laptops.

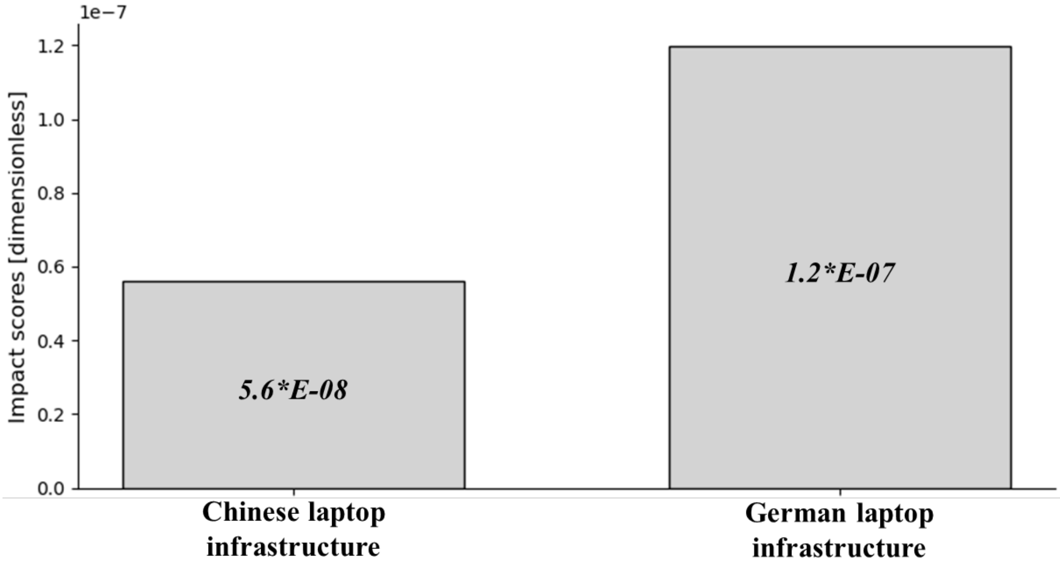

Figure 31: Comparison between different laptops considering cobalt stockpiles

The fourth group of material/product hotspots describes potential disruptions along the supply chain for nuclear power plant equipment. These disruptions particularly refer to hafnium flows. A way to avoid such supply risks is to shift from nuclear energy towards other sources of energy. Such a shift has for example been initiated recently in Germany by the closure of the country's final three nuclear power plants (Federal Office for the Safety of Nuclear Waste Management 2023). With regard to this shift, it is however necessary to analyze whether the impacts of implementing new technologies or supplying alternative fuels are relatively lower.

5.3 Conclusions on the assessment of Swiss mobility, energy and ICT sectors

This chapter presents a case study, where supply disruption impacts are for the first time assessed along the full supply chain on a sectoral level within the Life Cycle Sustainability Assessment framework (see section 5.2.5 for a comparison of results between our study and existing studies). In particular, a hotspot analysis and impact comparisons between key technologies have been performed in this case study based on the assessment of supply disruption impacts along global supply chains within the Swiss mobility, energy and ICT sectors with the SPOTTER approach. Similar to the first case study with SPOTTER (see Chapter 4), the goal and scope definition, the inventory analysis, the impact assessment and the interpretation phase related to SPOTTER have thereby been considered. In view of the tremendous efforts of data acquisition and computation for an assessment on a sectoral level, a screening procedure has additionally been implemented as an integral part of the goal and scope definition and inventory analysis. This screening procedure allows for identifying material/product flows influential for an assessment with SPOTTER. Flows occurring along supply chains of critical raw materials, relevant in terms of risk mitigation effects of country-specific safety stocks and associated with relatively high vulnerability and economic importance have thus been selected.

While such screening certainly has the advantage of a more practical analysis of material/product flows, thresholds applied for the screening should be carefully defined to avoid the exclusion of flows that are actually associated with relevant impacts. As the considered thresholds are determined based on only a single case study with SPOTTER (i.e. the one performed in section 4), the definition of these thresholds should be reviewed and potentially be refined by for example using sensitivity analysis. Furthermore, as explained in section 4.3, limitations exist regarding the quantification of the event probabilities and the high sensitivity to data availability and quality. These issues could be addressed by additional empirical studies and an extension of relevant databases.

Nevertheless, the results of this case study provide new information about supply risks on the level of the country-specific material/product flows at different supply chain stages that is helpful in gaining knowledge regarding the implementation of suitable mitigation measures. The results of the hotspot analysis related to material/product supply have for example suggested high impacts related to the imports of electronic devices from China as well as potential supply disruptions due to volatile prices of solar panels. Furthermore, these results have indicated high supply risks for cobalt, lithium, natural graphite, gallium, beryllium, battery cells and semiconductors used in emerging technologies such as lithium-ion batteries and solar panels as well as potential supply disruptions for hafnium powder, hafnium ore and nuclear power plant equipment. The results of the hotspot analysis related to fuel supply have suggested high risks of natural gas, coal, uranium and petroleum oil supply from Russia, Niger or Nigeria as well as potential supply disruptions in the global markets of uranium, coal and fuel wood. To demonstrate that these results can be used for the identification of risk mitigation measures, such measures suitable to mitigate the identified supply risks have finally been suggested.

Last but not least, the results of the impact comparisons have suggested relatively lower impacts associated with the utilization of certain key technologies. For example, lower risks have been identified for the implementation of wind turbines compared to solar panels and the supply of German laptops compared to Chinese laptops. Furthermore, the comparison between battery electric cars and conventional cars indicates comparably higher impacts for the infrastructure but relatively lower impacts for the fuels used in battery electric cars. These results are helpful to support the decision-making regarding the implementation of different technologies that provide the same service.

"If anything is certain, it is that change is certain.
The world we are planning for today will not exist in this form tomorrow."

~Phil Crosb

6. Discussion

Due to the dependency of the Swiss service-oriented economy on complex, global supply chains and the high risks of supply disruptions along these supply chains in the next years, there is a strong need to establish an effective resource strategy in Switzerland. Considering this need and the need to implement strategies for achieving the country's sustainable development goals, the assessment of supply disruption impacts within a sustainability assessment framework is of particular interest. This type of assessment has overall gained a strong interest in recent years as several countries increasingly aim to anticipate risks along their global supply chains and have ambitions towards achieving sustainable development goals (Hackenhaar et al. 2022; Sonnemann et al. 2015). As highlighted by Sonnemann et al. (2015), an interesting option in this direction is the integration of criticality assessment into the Life Cycle Sustainability Assessment (LCSA) framework. Such an integrated approach has, amongst others, the benefits that it allows for avoiding burden-shifting between different supply chain processes and between environmental impacts and supply disruption impacts (see section 1.3 for the list and explanation of benefits).

While some approaches assessing criticality within LCSA have already been developed and applied in different case studies, four major issues regarding the use of existing approaches for an evaluation of supply disruption impacts along global supply chains remain (see section 2.5). First, these approaches do not inform about potential supply disruptions along full supply chains, as they mostly analyze raw materials supply only. Second, they neglect medium-term impacts because of their focus on short-term impacts. Third, there is a risk of overlooking possible supply disruptions, as the representation of supply disruption events is often limited in the available approaches. Fourth, an assessment of supply disruption impacts on individual sectors of an economy is not possible, since the existing approaches focus on single products, individual companies or the aggregated supply chains of the entire economy in their assessments.

The in Chapter 3 described SPOTTER approach – a newly developed approach for integrating criticality assessment into the LCSA framework – overcomes the four issues listed above, as SPOTTER is an approach assessing supply disruption impacts along the full supply chain in the short- and medium-term. The development of this approach thus allows for answering the first research question. Following, the characteristics of

SPOTTER are discussed in comparison with other existing approaches. For this comparison, mainly the ESSENZ approach (Bach et al. 2016) and the GeoPolRisk approach (Gemechu et al. 2015b) including its extensions made by Helbig et al. (2016c) and Cimprich et al. (2017, 2018) are considered because, as mentioned in section 2.3, the developments of these two approaches describe the two main branches of developments in the field of criticality assessment within LCSA. An overview of the characteristics discussed in the following paragraphs is provided in Table 10.

Table 10: Overview of approach characteristics considering the SPOTTER (Chapter 3), GeoPolRisk (Cimprich et al. 2017; Cimprich et al. 2018; Gemechu et al. 2015b; Helbig et al. 2016c) and ESSENZ (Bach et al. 2016) approaches

Characteristics	SPOTTER	GeoPolRisk	ESSENZ
Objective	Analyze hotspots and determine overall impacts	Analyze hotspots and determine overall impacts	Analyze hotspots and determine overall impacts
Target audience	Product using country	Product manufacturing country	Multinational companies
Time horizon	Short-term and medium-term	Short-term	Short-term and medium-term
Scope of supply chain analysis*	Material/product flows along the supply chain	A single supply chain stage	A single supply chain stage
Product system	Country-specific supply chain of specific product	Raw material supply for specific product	Raw material supply for specific product
Geographical scope	Country	Country	Global
Impact categories	-Cost variability -Limited availability	-Increased cost of production -Impaired product function	-Limited availability -Reputational risk
Scope of events	-Five country-specific events -Five global events	One country-specific event	-Five country-specific events, -six global events -one company-specific event
Event selection procedure	Selection based on the analysis of frequently analyzed events	Selection based on the analysis of the most frequently analyzed event	Selection based on specific top-down and bottom-up approaches
Separation of short- and medium-term assessments	Yes	-	Partially

Table 10 (continued)

Characteristics	SPOTTER	GeoPolRisk	ESSENZ
Spatial resolution of characterization factors	National	National	Global
Supply chain resolution of characterization factors	Individual supply chain flows	Individual raw materials	Individual raw materials
Case-specific characterization factors	Yes	Yes	No
Raw material screening prior to assessment	Yes	No	No
Different supply chain models for short- and medium-term assessments	Yes	-	No

*A three-stage supply chain is modeled in GeoPolRisk extended by Helbig et al. (2016c). However, only the probability and not the impact of supply disruption is assessed in their approach.

Overall, the SPOTTER approach assesses the supply disruption impacts of each flow along the full supply chain individually with the objective to analyze hotspots and to determine the total impacts. The results then allow for highlighting supply risks that should be addressed with risk mitigation measures and for identifying technologies or supply scenarios associated with comparably low supply risks. Furthermore, SPOTTER evaluates impacts that are relevant over the next 5 years (i.e. short-term period) and in 5 to 15 years (i.e. medium-term period) with the objective of facilitating the identification of measures suitable to mitigate the impacts over these time horizons. ESSENZ and GeoPolRisk also provide assessments that allow for identifying hotspots and overall impacts of supply disruptions in the short-term as shown in the studies of Henßler et al. (2016), Sun et al. (2021) and Cimprich et al. (2017, 2018). However, these two approaches analyze only a single supply chain stage that is mostly related to the supply of raw materials as well as neglect the medium-term perspective. While GeoPolRisk extended by Helbig et al. (2016c) aims to address the issues of full supply chain coverage by analyzing material/product flows along a three-stage supply chain, this extension of GeoPolRisk represents hotspots of probability but not of the actual impact of supply disruption.

In SPOTTER, criticality is assessed by considering the supply chains of certain products involving processes in specific countries. In theory, SPOTTER could also be used to analyze supply chains that are specific to companies. Such an evaluation would be interesting for example in view of the German "Lieferkettengesetz" (Federal Ministry of Labour and Social Affairs 2021) and the "Corporate Sustainability Reporting Directive"

(European Commission 2022a), two legislations that require companies to report on their social and environmental risks as well as on the impacts of their activities on the environment and society. However, the applications of SPOTTER in this dissertation focus on country-specific supply chains of products to avoid the need for potentially confidential, company-specific information and to provide information suitable for designing resource strategies on the country level. According to Schrijvers et al. (2020b), criticality assessment could be conducted not only on a product- or company-level but also on the level of whole economies or at a global level. Analyses on these two levels are however not included in SPOTTER, as they would not offer sufficient material/product-specific and geographical information for an assessment along the supply chain. While SPOTTER considers the supply chain of a final product used in a country, the focus in GeoPolRisk extended by Cimprich et al. (2017, 2018) is on the raw material supply for a product manufacturing country. In ESSENZ in turn, the supply of individual materials (i.e. resources, minerals or raw materials) for a globally used product is analyzed. ESSENZ generally considers the global perspective but, as shown by Sun et al. (2021), the approach can also be adapted to a country perspective. In contrast to SPOTTER, GeoPolRisk and ESSENZ do not analyze interconnected supply chains but consider only a single supply chain stage that mainly represents the raw material supply. An exception is the GeoPolRisk extended by Helbig et al. (2016c), which allows for analyzing three-stage supply chains. However, as explained above, this extension is unsuitable for the evaluation of actual supply disruption impacts.

Frenzel et al. (2017) describe the effects of supply disruptions as *price hikes* that lead to higher costs and as *severe physical disruptions of supply* that lead to the unavailability of relevant materials/products, respectively. They further explain that price hikes cause physical disruptions when their effects are high enough. SPOTTER covers these two effects by evaluating the impacts of the categories *cost variability* and *limited availability*. Including both categories is deemed important, because, as shown by the examples regarding supply risk mitigation given by Alonso et al. (2007), knowledge about whether to expect higher costs that can potentially be passed on to customers or whether to prepare for unavailability by for example stockpiling or the identification of alternatives is pivotal for the decision-making. Similar to SPOTTER, the GeoPolRisk extended by Cimprich et al. (2017) differentiates between increased costs of production and impaired product function due to material unavailability. On the contrary, ESSENZ only considers limited availability and thus does not inform about variations in costs. Another type of impact considered in ESSENZ and BIRD (Bach et al. 2017a) for example is the effect of reputational damage. Reputational risks are however not evaluated in SPOTTER as they are rather relevant for assessments on company-level (Schrijvers et al. 2020b).

In SPOTTER, six events relevant in the short-term (i.e. *geopolitical instability*, *trade barriers*, *child labor restrictions*, *depletion of economic resources*, *price volatility* and *limited recyclability*) and four events relevant in the medium-term (i.e. *demand growth*, *co-product dependency*, *primary raw material reliance* and *depletion of ultimate resource*) are considered as being at the origin of the respective impacts. The first four of the listed short-term and the last one of the listed medium-term events are country-specific events, i.e. events that are specific to flows between different countries, while the remaining short- and medium-term events refer to global events, i.e. events for which equivalent impacts are expected around the world. The included events are among the ones most frequently considered in criticality assessment approaches as shown in Schrijvers et al. (2020b). These events are deemed relevant because they represent expert knowledge across the field on important causes for supply disruptions. In contrast to SPOTTER and ESSENZ, where several events are analyzed, GeoPolRisk only focuses on the event *geopolitical instability* and thus, bears a higher risk that impacts stemming from relevant events are neglected. For example, impacts due to fluctuating prices considered in SPOTTER and ESSENZ, are not assessed in GeoPolRisk. Assessing these impacts however seems of high relevance nowadays, particularly in view of the currently high inflation rates (Forbes 2023). The relevance to address the risks related to high inflation rates has for example become evident by the implementation of the "Inflation Reduction Act" that incentivizes, through a reduction of costs, the transition towards a clean energy economy (EPA 2023).

While some events are more frequently analyzed within criticality assessment approaches compared to others (see Figure 8), which events to consider and how to identify those events is widely debated in the field (Dewulf et al. 2016; Hatayama and Tahara 2018). In SPOTTER and GeoPolRisk, the events are selected based on an analysis of the most frequently analyzed events in the literature. In ESSENZ in turn, a more sophisticated selection procedure is applied based on bottom-up and top-down approaches that involve meta-criteria, correlation, relevance and data availability analyses. However, all these selection procedures are dependent on expert judgment to some extent, which, as criticized by Frenzel et al. (2017), reflects the bias of those experts. An alternative way of identifying relevant events is presented by Hatayama and Tahara (2018), who propose to select the events based on knowledge from empirical studies that reveal previous causes of supply disruption. They have applied such a case-based analysis to the example of metal supply from a Japanese perspective. However, one issue is that the results of their study are supposedly of limited relevance for studies focusing on other perspectives or other materials/products. Another issue is related to the retrospective characteristics of such case-based analyses as it may lead to missing information about causes of supply disruptions that will gain on relevance in the coming years. Examples of such causes could be potential restrictions due to the environmental or social policies, which are as shown by ESPAS (2019), OECD (2021), and European Environment Agency (2023) currently increasingly implemented.

SPOTTER assesses impacts separately for the short- and medium-term periods considering the above-mentioned events for the respective period. A clear separation of short- and medium-term impacts is deemed relevant because, as also explained by Ku et al. (2018), the implementation of effective risk mitigation measures varies between these time horizons. For example, supply chain diversification is considered suitable to mitigate immediate risks, while the implementation of effective substitutes requires time and is thus seen as a solution for the medium-term (Ku et al. 2018). In GeoPolRisk, only the short-term impacts caused by *geopolitical instability* are assessed. In ESSENZ, impacts stemming from short- and medium-term events are evaluated in parallel and the results are represented related to each event separately. Such a separate representation allows for making decisions specific to the individual time horizons. Making such decisions however becomes difficult when short- and medium-term impacts are aggregated and presented as a whole, as done in SCARCE (Bach et al. 2017b).

The impacts considered in SPOTTER are defined based on cause-effect chains that reflect the anticipated risks. In contrast to the *inside-out* cause-effect chains considered in conventional LCIA methods such as ReCiPe 2016 (Huijbregts et al. 2016), approaches integrating criticality assessment into the LCSA framework are concerned with *outside-in* relations (Cimprich et al. 2019). Within these approaches, the inventory flow amounts are multiplied with characterization factors (CFs) that define such *outside-in* impacts. These impacts describe the effects of changes in external conditions on the considered product system. The magnitude of impacts depends on how vulnerable the specific product systems are to these changes. This vulnerability may vary between different product systems. If then the vulnerability of the specific product system is considered in the calculation of the CFs, as is the case for example in SPOTTER and GeoPolRisk extended by Cimprich et al. (2017), the CFs are case-specific, meaning these CFs need to be newly calculated in each case study even when the same material is considered. If however the CFs define the vulnerability to supply disruptions generically on a global level, as done in ESSENZ, the CFs are not case-specific. Once defined, such generic CFs can be used for evaluating supply disruptions for the same materials across different case studies. However, these CFs do not allow for representing for example the economic importance of a raw material for the specific product system, which, as shown by Helbig et al. (2016a), is an important aspect of vulnerability analysis.

Considering the limited data availability for an assessment along the supply chain and the high efforts required for the definition of case-specific CFs, Chapter 3 describes a procedure that illustrates and simplifies the assessment with SPOTTER called the 'SPOTTER implementation procedure'.

One key element of this procedure is the suggestion of a screening of raw materials based on lists of critical raw materials for a specific country/region. Such screening is for example performed in the EU Foresight Studies (Bobba et al. 2020; Carrara et al. 2023), where raw materials are selected based on the list of critical raw materials published by the European Commission (2020c). The screening of raw materials prior to the assessment also plays an important role in the approach of Kolotzek et al. (2018). They perform a vulnerability analysis based on expert judgment to identify the relevant raw materials. While such screening techniques are helpful to reduce the efforts related to the assessment, they presume the validity of results from prior evaluations.

Another key element of the 'SPOTTER implementation procedure' is the recommendations regarding the use of supply chain models for short- and medium-term assessments. According to this recommendation, at least two different supply chain models, one informing on flows in the short-term based on recent production and/or trade amounts and another one reporting flows in the medium-term based on future trends, need to be defined. This way of supply chain definition contradicts ESSENZ, where recent production amounts are used to inform on both, flows in the short-term and flows in the medium-term. In ESSENZ, lower efforts are thus inevitably required for the definition of supply chain models in the two time horizons. It is however questionable, whether recent production amounts are suitable to inform on flows over the medium-term period, as these production amounts may change in the coming years.

Additionally, Chapter 3 explains the identification and definition of the indicators used in SPOTTER in order to calculate the CFs considered for the evaluation of supply disruption impacts within LCSA. To identify indicators suitable for use in SPOTTER, cause-effect chains that describe supply disruption probability and vulnerability are first defined and, following the suggestion of Schrijvers et al. (2020b), indicators that represent the probability and vulnerability factors within these cause-effect chains are then selected. The selected indicators comprise the indicators for supply disruption event over a period (EI*t) and supplier diversity (DI), i.e. two indicators that represent supply disruption probability, as well as the indicators for vulnerability to physical shortage (PVI) and economic importance/damage (EVIs), i.e. two indicators that describe the vulnerability.

In the following paragraphs, the indicator definition in SPOTTER is discussed and compared to the definitions in ESSENZ (Bach et al. 2016) and GeoPolRisk extended by Cimprich et al. (2017). This extension of GeoPolRisk is considered for the comparison because, out of the different extensions of GeoPolRisk (see Table 2), it describes the most crucial development towards a characterization model that allows for assessing supply disruption impacts with GeoPolRisk. Table 11 provides an overview of indicator definitions used in the three approaches.

Table 11: Overview of indicator definitions in different approaches
considering the SPOTTER, GeoPolRisk extended by Cimprich et al. (2017) and ESSENZ (Bach et al. 2016) approaches. The definitions of the indicators for geopolitical instability are compared because it is the only event that is considered in all three approaches.

Indicators	SPOTTER	GeoPolRisk	ESSENZ
Indicator for geopolitical instability*	WGI - Political Stability and Absence of Violence/Terrorism	WGI - Political Stability and Absence of Violence/Terrorism	All six WGIs, equally weighted
Indicator for supplier diversity**	-Import share complemented with domestic production amount (country-specific events) -Ratio of country-specific production amount to global production amount (global events); ratio determined based on HHI	-Import share complemented with domestic production amount -Ratio of country-specific production amount to global production amount; ratio determined based on HHI	-Ratio of country-specific production amount to global production amount; ratio determined based on production shares
Indicator for vulnerability to supply disruption	-Ratio between global production amount and in-use stock of the material/product squared -Ratio between the economic value of material/product flow and the total economic value of the material/product in the supply chain	<u>One option:</u> -1 divided by raw material flow amount <u>Another option:</u> -Ratio between the economic value of the raw material and the economic value of tungsten (i.e. reference material)	-1 divided by global production amount of the material

*The Worldwide Governance Indicators (WGIs) provided by the World Bank (2019) are commonly used to define geopolitical instability. **The Herfindahl-Hirschman Index (HHI) (Herfindahl 1950; Hirschman 1945) is used to evaluate production concentration in SPOTTER and GeoPolRisk, while production shares are used in ESSENZ.

SPOTTER defines DI, PVI and EVI in terms of allowing for the assessment of the full supply chain. As seen in Table 11 and when comparing the Equations (11)-(18) with the Equations (6) and (7), the indicator definitions in SPOTTER differ from the ones in GeoPolRisk extended by Cimprich et al. (2017) and the ones in ESSENZ. To define supplier diversity, all three approaches consider production concentrations. SPOTTER and the extended GeoPolRisk additionally consider import concentrations. In contrast to the other two approaches, SPOTTER distinguishes in these definitions between country-specific events that affect a flow between two countries and global events that refer to potential supply disruption in the global market. Regarding the PVI and EVI definitions, SPOTTER interprets high vulnerability with the existence of relatively large global production amounts compared to the global in-use stocks and with the economic value of the material/product flow in the supply chain. In contrast, ESSENZ describes high vulnerability by low global production amounts. In the GeoPolRisk extended by Cimprich et al. (2017) in turn, it is assumed, in one embodiment, that the disruption of each raw material flow has the same impact on the product system and, in another embodiment, that the vulnerability of the product system is dependent on the economic value of its used raw materials.

In SPOTTER, ten different EIs are used to represent the considered events. Indicators for the same events vary between SPOTTER, GeoPolRisk and ESSENZ. For example, different types of Worldwide Governance Indicators (WGIs), indicators provided by the World Bank (2019) defining the quality of governance, are used to represent geopolitical instability within the three approaches (Table 11). On the same note, the review paper of Achzet and Helbig (2013) shows that also in several other cases, a specific supply disruption event is described with different indicators. This is because there is no consensus on which indicators adequately represent the respective events and the indicators are then mostly selected based on subjective opinions (Erdmann and Graedel 2011; Frenzel et al. 2017). Limiting the influence of expert/author judgment in the indicator selection would however be relevant to provide results that are defendable against criticisms regarding the reflection of expert biases (Schrijvers et al. 2020b). To limit the influence of subjective judgment in SPOTTER, heuristics are applied to justify the selection/adaption of indicators that are used in the approach. Hence, all the indicators selected/adapted for the use in SPOTTER are suitable for (i) avoiding burden-shifting between impacts along the supply chain, (ii) quantitatively assessing short- and medium-term impacts, (iii) facilitating the identification of origins of supply disruptions, (iv) providing reproducible results and (v) allowing for a consistent interpretation of results.

The application of these heuristics described above ensures a more transparent indicator selection. However, it is still debatable whether the initially collected indicators that serve as the basis for the selection process realistically represent the supply disruption events. An example is the discussion regarding which of the six WGIs and whether the WGIs after all are suitable to represent geopolitical instability (Kaufmann et al. 2010a; Langbein and Knack 2010). Another example, already discussed in section 2.1.3, is the issue of how to assess impacts related to the use of natural resources. Here, an expert task force particularly established to reflect on this topic has not been able to provide a universal solution (Berger et al. 2020; Sonderegger et al. 2020).

Within the Chapters 4 and 5 of this dissertation, SPOTTER is applied in the first case studies and this thus allows answering the second and third research questions. A challenge during the application of SPOTTER has been the identification of suitable data sources to quantify the flows along the supply chain. The database *ecoinvent*, a database commonly used in process-based LCA studies (Wernet et al. 2016), has been evaluated as unsuitable to provide sufficient geographical and temporal information as well as datasets to cover all relevant processes along supply chains. A solution that allows for the quantification of the considered supply chain flows has however been identified in complementing ecoinvent data with trade data provided by BACI (Gaulier and Zignago 2010). Flows of several materials/products that are relevant in the two case studies could thus be covered (see list of materials/products in Appendix B.3 and C.1). However, flows of some relevant materials/products could still not be quantified because related trade data is not reported in BACI. As shown in section 5.1.1, an example of this issue is the flows of nickel-metal hydride batteries used in electric vehicles.

Another challenge during the application of SPOTTER has been the identification of the way that allows for quantifying material/product flows along product-specific supply chains. Here, a procedure has been developed, where flows are successively defined upstream of the supply chain starting with the flows of final products, continuing with the flows of intermediate products and raw materials and ending with the flows of minerals. This quantification procedure differs from the procedure applied by Helbig et al. (2016c), where the material/product flows along the supply chain are quantified by going the other direction (i.e. starting with flows of minerals and ending with flows of final products). However, it has not been possible in their assessment based on this kind of supply chain analysis to establish a link to the functional unit, which, as described in section 2.1.2, is a central concept in LCA or LCSA.

A third challenge particularly related to the case study performed in Chapter 5 has been the data acquisition and computation effort that is required for the analysis of material/product flows in an assessment on a sectoral level. These efforts are very high when following only the 'SPOTTER implementation procedure' because a huge number of material/product flows would need to be analyzed. Hence, to reduce the number of flows to be considered for the analysis and thus the data acquisition and computation efforts, an additional screening procedure that allows for selecting the material/product flows influential for the assessment with SPOTTER has been introduced. A key element of this screening procedure is the selection of material/product flows that are used in significant amounts and that are particularly vulnerable to physical shortage and economically important/damaging for the product system. Thresholds used for this screening are defined based on values that describe hotspots in the first case study with SPOTTER (see Chapter 4). While such screening certainly has the advantage of a more practical analysis of material/product flows, the thresholds applied for the screening should be carefully defined to avoid the exclusion of flows that are actually associated with a relevant impact. However, only limited knowledge regarding the definition of these thresholds so far exists due to the currently small number of case studies performed with SPOTTER.

In the following paragraphs, key findings of our two case studies performed with SPOTTER – the first one focusing on the cobalt and aluminium supply chains of EVs used in Switzerland and the second one considering the global supply chains of the Swiss mobility, energy and ICT sectors (see details described in the Chapters 4 and 5) – are discussed and also reflected in view of the results of other existing studies.

First, several congruent hotspots for cost variability and limited availability (i.e. the two considered impact categories in SPOTTER) are identified in the two case studies. Such a correlation between cost variability and limited availability is also found in the study performed by Cimprich et al. (2017) using the extended GeoPolRisk approach, as they show for example that impacts of neodymium makes up the highest contribution to both impact categories, respectively. Congruent impacts mean that it is not clear whether the indicated potential supply disruptions lead to a price hike resulting in higher costs or severe physical disruptions causing limited availability. A clearer division of impacts between these two categories could be achieved by considering the effect sizes because, as stated above, if effect sizes of price hikes are high enough these higher prices lead to severe physical disruptions. However, as stated by Frenzel et al. (2017), information about effect sizes is currently widely missing in the literature.

Secondly, disrupted flows of cobalt are identified as one of the major reasons for potential supply disruptions along supply chains of LIBs used in EVs and electronic devices. Overall, the supply of cobalt has been identified as critical in many of the existing criticality studies as shown in the reviews conducted by Schrijvers et al. (2020b) and Hayes and McCullough (2018). Similar to our case studies, some of these studies have also highlighted the criticality of cobalt in the supply chains of LIBs used in EVs or electronic devices (Bobba et al. 2020; Carrara et al. 2023; Helbig et al. 2018; Sun et al. 2021). However, in contrast to most of the existing studies, our case studies indicate country-specific flows that are potentially disrupted along the mining, processing and refining stages of the cobalt supply chain instead of only describing the criticality of the cobalt raw material. Such more detailed information regarding the criticality of cobalt is helpful to identify where the actual risks of supply disruption lie along the supply chain and then to enable a response to these risks by the countries consuming cobalt (e.g. through implementing stockpiles, through restructuring and diversifying the supply chain or through concluding long-term contracts with producers). In contrast to our and several other studies that analyze supply disruption hotspots for EVs (see above), the studies of Cimprich et al. (2017, 2018) and Lütkehaus et al. (2022) do not include cobalt in their analysis at all. This is odd because cobalt is not only frequently rated as critical but also seen as a crucial material in the cathode of current traction batteries (Nature Editorial 2021). A reason why cobalt is disregarded in their studies probably is that their analysis of raw material flows relies on a model of EVs provided by Hawkins et al. (2012) who have considered a lithium-ion manganese oxide battery instead of the nowadays commonly used lithium-ion battery.

Third, several potentially disrupted flows of materials/products and fuels between different countries are identified as hotspots in our studies. The hotspots related to material/product flows show that supply disruption events occurring mainly in Asian, African or other developing countries affect the production processes and consumption of Western or Asian economies. Besides the impacts of cobalt mentioned in the previous paragraph, the impacts of electronic devices as well as the impacts of materials/components used in LIBs, nuclear power plants and solar panels thereby describe the main contributors to the overall impacts on the product system. The hotspots related to the flows of fuels indicate the relatively highest supply risks for uranium, natural gas, coal and petroleum oil from Russia, Niger and Nigeria. The detailed information about potentially disrupted material/product or fuel flows along the supply chain that is provided in our case studies is deemed relevant in terms of decision-making regarding the implementation of risk mitigation measures. For example, effective restructuring of supply chains or concluding long-term contracts with producers are difficult to put into practice when the most critical flows along the supply chain are not known. Such detailed information is however widely missing in other studies. A reason is, as mentioned by Cimprich et al. (2019), the enormous efforts in data collection and computation for assessments along supply chains. Studies that however analyze hotspots of materials/products along the supply chain for different technologies are the EU Foresight Studies (Bobba et al. 2020; Carrara et al. 2023). Similar to our study, these Foresight Studies indicate the dependency on the supply of some key technologies such as solar panels, LIBs, mobile phones and laptops from China as well as suggest high risks related to cobalt, lithium, natural graphite, gallium and borates supply. However, an issue regarding hotspot analysis of full supply chains with the EU Foresight Studies is that they only analyze imports into European countries and thus do not inform about impacts related to flows along the upstream supply chains. The relatively large cobalt flow between China and Congo is thus for example not considered. Furthermore, these studies do not allow for an analysis of risks related to fuel supply, which however seems relevant particularly in terms of the recent energy crisis in Europe (IEA 2023). Finally, the EU Foresight Studies are not integrated into the LCSA framework and thus miss the benefits of this integration such as the avoidance of burden-shifting between different types of impacts (see an explanation of benefits in section 1.3).

Fourth, several potential supply disruptions in the global market of materials/products and fuels, which stem from price volatilities, limited recyclability and/or high production concentrations, are identified as hotspots in our study. These supply risks are suggested especially for mobile phones, solar panels, materials/components of LIBs and solar panels as well as coal, uranium and fuel wood. Sun et al. (2021) have also assessed potential supply disruption impacts focusing on raw materials and fuels used in EVs and internal combustion engine vehicles. While they have, similar to our case study, identified for example relatively high impacts due to the price volatility of coal, many of their results differ from the ones of our study. In contrast to the results of the study conducted by Sun et al. (2021), which suggest particularly high impacts of iron and petroleum oil, the results of our study indicate high supply risks due to price variations for uranium, fuel wood, natural graphite, lithium ore, lithium powder and beryllium powder. One reason for these differences could be the different geographical scopes of the studies. While our case study analyzes supply chains from a Swiss perspective, Sun et al. (2021) consider the supply chains of China. Another reason could be that their study focuses on raw materials, while our study analyzes flows along the full supply chain. A third reason could be the differences in the inclusion of raw materials. For example, beryllium and iron are only considered in one of the two studies, respectively. A fourth reason could be that the fuel supply of the mobility, energy and ICT sectors are analyzed in our study, while only the fuels used in the mobility sectors are considered in the study of Sun et al. (2021). In the EU Foresight Studies (Bobba et al. 2020; Carrara et al. 2023) and studies based on GeoPolRisk (Gemechu et al. 2015b) in turn, impacts stemming from global events have not been assessed at all. However, as stated above, particularly the analysis of global price volatilities seems relevant nowadays considering the high inflation rates (Forbes 2023).

Fifth, high supply risks are suggested related to the supply chains for emerging technologies such as EVs and solar panels. The identified supply disruption hotspots indicate for example potential disruptions for the supply of cobalt, lithium, natural graphite and lithium-ion batteries used in EVs as well as for the supply of gallium, beryllium and semiconductors used in solar panels. One reason for the occurrence of hotspots along supply chains for emerging technologies is the high vulnerability to physical shortages of the used materials/products. These shortages can often not easily be compensated by the supply of EoL products because the in-use stocks of these materials/products are generally low compared to demand. These concerns are also apparent in several other criticality studies because, as shown in the review article published by Jin et al. (2016), a major part of the existing literature on criticality assessment focus on the supply of raw materials used in emerging clean technologies. While the case studies with SPOTTER and existing criticality studies mainly identify hotspots in the supply chains for such technologies, recent events have shown that severe supply disruptions may also occur along the supply chains for established technologies. An example is the current shortage of semiconductors used in vehicles (J.P.Morgan 2023). One of the reasons for this chip shortage is supposedly the complex recycling processes and the widely missing regulations for treating EoL car electronics (Restrepo et al. 2020) so that vehicle chips are not possible to be sufficiently recovered from EoL products. Potential shortages of car electronics however have not been identified in our case studies because the issue regarding the sufficient recoverability of materials from EoL products has so far not been considered in SPOTTER.

"We cannot solve our problems with the same thinking we used when we created them"

~ Albert Einstein

7. Conclusion and Outlook

This doctoral thesis assesses potential supply disruption impacts along global supply chains of the Swiss economy within the Life Cycle Sustainability Assessment (LCSA) framework. The work has started with the development of a new approach, called SPOTTER, to address the issue of full supply chain coverage in the field of criticality assessment within LCSA. SPOTTER has then been applied in two different case studies, one focusing on the short-term assessment of electric vehicles (EVs) used in Switzerland and another one evaluating impacts on the mobility, energy and ICT sectors within the Swiss economy in the short-term. These two case studies have indicated different supply disruption hotspots along global supply chains and have identified relevant technologies associated with comparably low supply risks. The following four paragraphs summarize the main results of this thesis by describing the outcomes of the research questions 1 to 3 stated at the beginning of the thesis:

RQ1. With the development of SPOTTER, a novel way has been proposed to quantitatively assess potential supply disruption impacts along the supply chain in the short-term (i.e. the next 5 years) and medium-term (i.e. in 5 to 15 years) within the LCSA framework. SPOTTER allows for analyzing supply disruption hotspots based on key supply bottlenecks (i.e. relatively highest impact scores) and for assessing the overall impacts of the product system based on the sum of impact scores. The calculation of the impact scores is performed by multiplying the amounts of the individual inventory flows with the respective characterization factors (CFs) defining the supply disruption impact. The inventory flow amounts are defined by analyzing material/product flows that occur between country-specific supply chain processes. The CFs in turn are defined by describing cause-effect chains between the considered events and impacts of supply disruption. The relevant events have been identified based on an analysis of frequently analyzed events in criticality assessment approaches. These events comprise the short-term events *geopolitical instability*, *child labor restrictions*, *trade barriers*, *price volatility*, *limited recyclability* and *depletion of economic resources* as well as the medium-term events *demand growth*, *co-product dependency*, *primary raw material reliance* and *depletion of ultimate resources*. The assessed impact categories have been defined as *cost variability* and *limited availability*. The evaluation of included impacts is context-dependent (i.e. dependent on the state of the considered product system) and, as the state of product systems commonly varies, the calculated CFs are case-specific. Given the high efforts linked to the definition of case-specific CFs and the limited data availability for an assessment along the full supply chain, a procedure to simplify the assessment with SPOTTER has been suggested. This procedure, called the 'SPOTTER implementation procedure', involves guidelines regarding the definition of the scope, the analysis of the life cycle inventory, the screening of the inventory flow relevance, the definition of the temporal relevance and the calculation of CFs.

Indicators of supply disruption probability and vulnerability have been used to calculate the CFs considered in SPOTTER. The probability indicators comprise indicators for supply disruption events over a period (*EIs*t*) and indicators for the diversity of supply (*DIs*). The definition of these *EIs*t* is based on ten indicators representing the different supply disruption events listed above, respectively. The *DIs* are defined by measurements of supply concentration related to the individual material/product flows along the supply chain. The vulnerability indicators comprise indicators for vulnerability to physical shortage (*PVIs*) and indicators for economic importance or economic damage (*EVIs*). The *PVIs* are defined by a relationship between the global production amount and the global in-use stock. The *EVIs* describe the economic value of the material/product flow in the supply chain. The *DIs*, *PVIs* and *EVIs* have been selected/adapted from existing approaches considering their suitability for an assessment along the full supply chain. The *EIs* in turn have been identified based on a heuristic diagram, which allows for selecting/adapting indicators collected from the literature that are suitable to represent the events considered in SPOTTER.

RQ2. In the next step, the application of the SPOTTER approach has been demonstrated by using the 'SPOTTER implementation procedure' in a first case study where potential supply disruption impacts are evaluated on a product-level. Specifically, the short-term impacts of potential supply disruptions along the cobalt and aluminium supply chain of EVs used in Switzerland have been assessed in this case study. The objectives of this assessment are a hotspot analysis and the determination of overall impacts. The assessment has been performed in relation to the functional unit described by the electric car fleet of Switzerland in 2019. First, the procedure used for the inventory analysis has been demonstrated, where the material/product flow amounts are defined upstream along the supply chain in relation to the functional unit. Then, the way to calculate impact scores described in the sections 3.2.1 to 3.2.3 has been illustrated by the example of the calculation of impact scores for a cobalt powder flow and a cobalt ore flow within the supply chain. Finally, the way of interpreting results has been explained by the definition of supply disruption hotspots through impact scores that are higher than 1% of the overall impact score. The identified hotspots suggest that supply disruption events mainly occur globally or in developing countries and affect Western or Asian economies. On the one hand, supply disruptions stemming from country-specific events may occur related to Swiss EV imports from the USA, flows of EV wiring from Mexico to the USA and flows of cobalt ore from Congo to China. On the other hand, supply disruptions on the global market of cobalt powder and different components of EVs and batteries may affect EV manufacturing in the USA and manufacturing of traction batteries in Asia. Last but not least, a comparison of the presented results with the results of existing studies has shown that the performed hotspot analysis provides new information about relevant supply risks along the full supply chain. It has then been demonstrated how this new information can support the decision-making regarding supply risk mitigation. The indicated supply risks have therefore been split into three different groups and measures targeted to policy-makers and Swiss EV retailers have been suggested that allow for mitigating the supply risks covered by these groups.

RQ3. To identify relevant supply risks along global supply chains for entire sectors, a second case study with SPOTTER has been performed on the Swiss mobility, energy and ICT sectors. In this case study, supply disruption hotspots have been analyzed considering a combination of the three sectors and each of them individually as well as overall impacts have been compared between competing technologies used in the three sectors. The functional units have been defined, for the hotspot analysis, based on the amounts of fuels and final products used in the three Swiss sectors in 2020 and, for the impact comparisons, based on the same service or number of products related to competing technologies. For the performance of the case study, the 'SPOTTER implementation procedure' in combination with an additional screening procedure has been used in order to further reduce the efforts regarding data collection and computation. This here-introduced screening procedure allows for selecting, in five steps, the material/product flows most influential for the assessment with SPOTTER. The first three steps of the procedure describe the selection of a set of materials/products including critical raw materials and their related intermediate/final products for which suitable trade data is available. The fourth and fifth steps then allow for identifying the relevant flows of materials/products included in the set of prior selected materials/products by considering country-specific safety stocks of final products and the most vulnerable and economically important material/intermediate product flows. The results of the hotspot analysis suggest four groups of key supply risks. The first group includes the risks related to the imports of electronic devices from China and the supply of natural gas, uranium and petroleum oil from Russia, Niger and Nigeria. The second group covers potential supply disruptions in the global market of solar panels, coal, uranium and fuel wood. The third group comprises risks related to the supply of materials/components used in emerging technologies such as lithium-ion batteries (LIBs), solar panels or wind turbines. These materials/components include, amongst others, cobalt, lithium, natural graphite, gallium, beryllium, borates, magnesium, battery cells, semiconductors and permanent magnets mainly produced in Asian and African countries and mainly used for production processes in Asia. The fourth group covers potential disruptions of hafnium supply and the supply of equipment used in nuclear power plants. Considering the results of the hotspot analysis split into these four groups, different measures have been suggested that are suitable to mitigate supply risks for the Swiss economy. The results of the impact comparison between electric battery cars and conventional cars indicate higher supply risks for infrastructure and lower supply risks for the fuels used in battery electric cars. Furthermore, the comparisons between solar panels and wind turbines as well as between Chinese and German laptops suggest higher risks for the installation of solar panels and the supply of laptops produced in China. Finally, a comparison made between the presented results and the results of existing studies has shown that some of our results confirm the ones of existing studies but also that the performed hotspot analysis and impact comparisons provide new information about relevant supply risks within the mobility, energy and ICT sectors of an economy. Providing this new information is possible mainly due to a more comprehensive analysis of the supply chain and supply disruption events as well as due to the consideration of infrastructure and fuels used in entire sectors.

As shown in this dissertation, the development of the SPOTTER approach describes a significant contribution to the assessment of supply disruption impact within the LCSA framework. However, limitations linked to the methodology and application of SPOTTER as well as the research related to assessments with SPOTTER have to be considered. Possibilities to address these limitations by future research are presented in Figure 32. The identified future research directions comprise *improvements of the SPOTTER methodology*, *research needs to support the assessments with SPOTTER* and *opportunities for additional application of SPOTTER*.

Figure 32: Potential future research directions

<u>Improvements of the SPOTTER methodology:</u>

Performance of uncertainty analysis. Understanding the uncertainty in the outcomes of an LCSA is crucial in order to prevent decisions based on misleading findings (Gemechu et al. 2015b; Lloyd and Ries 2007). However, an estimation of variations of the calculated impact scores is missing in SPOTTER. To tackle this issue, a procedure that is similar to the uncertainty analysis presented by Gemechu et al. (2015b) or Helbig et al. (2016b) could be implemented. Such a procedure could first evaluate data qualities related to each of the indicators used for the calculation of impact scores and then perform a Monte Carlo simulation, a method for uncertainty propagation. Data qualities are already estimated for a few indicators such as for the Worldwide Governance Indicators, for which a justified distribution function is provided by Kaufmann et al. (2010b). However, as mentioned by Schrijvers et al. (2020b), information about data qualities is usually missing in the literature. Missing uncertainties could be evaluated using the Pedigree matrix developed by Graedel et al. (2012). This matrix, which is based on previous developments of uncertainty analysis in LCA performed by M. Goedkoop et al. (2007), is explicitly designed for evaluating uncertainties within criticality assessments (Gemechu et al. 2015b). For the subsequent Monte Carlo simulations, a lognormal distribution and random probabilities could be considered. An issue linked to such an uncertainty analysis could however be the high efforts in defining the data qualities for inventory flow amounts and indicators for economic importance/damage. Here, an analysis of uncertainties at each stage of the supply chain and an accumulation of uncertainties along the supply chain would be required.

Modeling of endpoint indicators. SPOTTER indicates supply risks in the form of relative impact scores with dimensionless units presented at the midpoint level. The interpretation of such dimensionless impact scores can however be challenging for decision-makers. As also highlighted by Santillan et al. (2020), the development of an appropriate endpoint indicator could be a way to provide less differentiated and complex results or allow for a better comparison of results. Future research could thereby build on previous advancements. Dewulf et al. (2015b) have for example conceptualized *human welfare* as an endpoint comprising all kinds of socio-economic impacts that materials/products have along the supply chain. Furthermore, Santillan et al. (2020) have operationalized an endpoint indicator considering the potential increased costs caused by geopolitically driven supply disruption of raw materials.

Inclusion of end-of-life recovery rate. Some potential physical shortages of materials/products may not be identified with SPOTTER because it disregards that some materials are currently not possible to be effectively recovered from end-of-life (EoL) products (as described in the section 6 by the example of electronics of EoL vehicles). This may lead to neglecting potential supply disruption impacts. To address this issue, information regarding EoL recovery rates could be collected from the literature (e.g. from the study of Merkisz-Guranowska (2018), which reports EoL recovery rates for vehicle components) and this information could then be considered for the definition of the indicator for vulnerability to the physical shortage.

Refining of the event coverage. SPOTTER comprises events that are frequently analyzed in criticality assessment approaches. However, frequent analysis of these events does not necessarily mean that all events actually responsible for supply disruptions are addressed. For example, environmental policy restrictions have not been considered a frequent event during the development of SPOTTER. However, considering the recent implementation of an increasing number of environmental policies (ESPAS 2019; European Environment Agency 2023; OECD 2021), the consideration of such restrictions is likely of increasing importance in terms of an assessment of supply disruption impacts. A way to improve the coverage of supply disruption events in SPOTTER could be to identify relevant supply disruption events based on expert judgment, empirical studies and/or media analysis, then the comparison of these events with the currently covered events and finally potential refining of the event coverage. Such a refining of event coverage should consider besides the evaluation regarding the relevance of events also whether the events could be represented with suitable indicators to ensure the practicability of the assessment.

Research needs to support the assessments with SPOTTER:

Improvement of event identification. In most of the criticality assessment approaches, expert judgment is used to identify and select the considered supply disruption events. However, as the consulted experts may not be aware of or may overlook some events, there is a risk that relevant supply disruption impacts are not assessed. To improve the way of identifying relevant events, Hatayama and Tahara (2018) suggest selecting events based on objective perspectives and subjective viewpoints. The knowledge for an objective perspective could thereby be gained through the performance of empirical studies about supply disruption events. Such an empirical study focusing on events that led to disruptions in metals supply has already been performed by Hatayama and Tahara (2018) from a Japanese perspective.

Refining of indicators used for event analysis. The developed indicators currently used in criticality assessment approaches may not adequately represent the supply disruption events. As illustrated in section 6, the representations of geopolitical instability and resource depletion for example are debated. Furthermore, the currently applied indicator scales may not refer to consistent probabilities for the occurrence of different events. An example would be if the indicator score of 0.8 for geopolitical instability and the indicator score of 0.8 for trade barriers do not refer to the same probability of event occurrence. To address these issues, as described in section 4.3 for the example of resource depletion indicators, empirical studies could be performed in collaboration with relevant stakeholders and then the definition and scaling of indicators could be refined based on the results of these studies.

Extension of relevant databases. The quality of the results provided by SPOTTER is highly sensitive to the availability and the quality of the required data. Data availability and quality could be improved by extending the databases used in criticality assessment and LCSA with more detailed material/product flow information. An example of a useful extension in the past was the inclusion of import/export amounts for electric vehicles in the latest version of the BACI database (the different versions of BACI can be found under this link), a crucial data source used for the assessment along the supply chain with SPOTTER. Furthermore, the CFs used in SPOTTER need to be calculated individually for each case study, as the indicator for economic importance/damage is case-specific. Hence, in order to reduce these efforts, lists of context-independent values could be created for all other indicators included in the CFs (i.e. lists comprising the unscaled values of the indicators for supply disruption events over a period and the indicators for the diversity of supply as well as the values of indicators for vulnerability to physical shortage).

Analysis of mitigation measure feasibility. Our study suggests the implementation of different measures to mitigate the supply risks identified with the performed hotspot analysis (see sections 4.2.5 and 5.2.6 for the description of these suggestions). Other studies such as the one performed by Sprecher et al. (2017b) also use the results of their analysis to make suggestions for risk mitigation. However, it often remains unclear whether the implementation of the suggested measures is technically feasible. In order to inform about technical feasibilities, follow-up studies could analyze prerequisites related to the implementation of these measures in the real world. For example, it would need to be analyzed whether decision makers have enough knowledge about (potential) suppliers/producers to be able to restructure supply chains or conclude long-term contracts and whether sufficient storage capacities are available to allow for the construction of stockpiles.

<u>Opportunities for additional applications of SPOTTER:</u>

Performance of medium-term assessments. SPOTTER has so far only been applied in case studies focusing on short-term assessments. However, the approach also allows for an assessment of supply disruption impacts in the medium-term, which could thus be performed in future studies. For example, a case study focusing on the Swiss mobility sector would be particularly interesting given the expected rapid implementation of electric vehicles in Switzerland in the coming years and the thus increasing dependency of the country on critical raw materials and high-tech products such as lithium-ion batteries. Four future scenarios that could be used in such a case study for the definition of relevant supply chain models have already been designed within our work. An overview of these scenarios is provided in Figure 33. For the definition of the scenarios, on the one hand, potential changes in the demography and consumer behavior (i.e. vehicle-per-capita rate) in Switzerland are assumed. The demographic changes are determined based on information from the Bundesamt für Statistik (2022b). The vehicle-per-capita increase is estimated considering the development in the past 20 years reported by the Bundesamt für Statistik (2022a) and the vehicle-per-capita decrease is estimated using logistic regression analysis. On the other hand, the development of the Swiss fleet of battery electric vehicles, plug-in hybrid electric vehicles, hybrid electric vehicles and internal combustion engine vehicles until the year 2040 is determined based on an expert workshop with "Auto Recycling Schweiz" in May 2022 and technology roadmaps published by McKinsey & Company (Eddy et al. 2019) and Bloomberg (Henze and Thomas 2017).

Technology type / Demography & vehicle amount	*Experts "Auto Recycling Schweiz"* • ~97% of BEC in 2040 • face out of PHEC in 2036 • face out of HEC in 2027 • ~3% of ICEC in 2040	*McKinsey & Company and Bloomberg* • ~67% of BEC in 2040 • ~5% of PHEC in 2040 • ~11% of HEC in 2040 • ~17% of ICEC in 2040
Demographic increase of ~16% and vehicle-per-capita increase of ~4% until 2040	**Scenario 1: "Fast electromobility transition & Increasing vehicle fleet"**	**Scenario 3: "Slow electromobility transition & Increasing vehicle fleet"**
Demographic increase of ~9% and vehicle-per-capita decrease of ~17% until 2040	**Scenario 2: "Fast electromobility transition & Decreasing vehicle fleet"**	**Scenario 4: "Slow electromobility transition & Decreasing vehicle fleet"**

Figure 33: Description of scenarios for the Swiss mobility sector until the year 2040.
The basis (i.e. situation in the year 2021) is defined by a population of ~8.67 Mio people, a vehicle-per-capita ratio of ~0.54 and the following shares of car types in the Swiss passenger vehicle fleet ~13% of battery electric cars (BECs), ~9% of plug-in hybrid electric cars (PHECs), ~23% of hybrid electric cars (HECs) and ~55% of internal combustion engine cars (ICECs).

In a next step, material/product flows along the supply chain would need to be quantified considering the four different scenarios and impact scores would need to be calculated by multiplying the flow amounts with the respective CFs suitable for the medium-term assessment.

Analysis of supply chain resilience. Another interesting opportunity for the application of SPOTTER would be to assess the impacts related to specific flows along the supply chain before and after the disruption of these flows. It could thus be analyzed whether the supply chain has become more resilient through the response to the considered supply disruption. To perform such an analysis, material or product flows that have been disrupted in the past would first need to be identified and then the impacts on these flows would need to be assessed and compared before and after the supply disruption.

Comparison of different supply scenarios. The overall supply disruption impacts assessed with SPOTTER have already been used to compare impacts between different technologies (see section 5.2.4). However, the assessment of overall impacts could also be used to compare different supply scenarios, which would allow for identifying scenarios associated with the comparably lowest supply risks. As already suggested in section 4.3 by the example of supply chains for EVs, different structures of the supply chain or the supply situations of different countries could be compared.

Application on company-level. So far, SPOTTER has not been applied to company-specific supply chains mainly due to concerns regarding access to company-specific data. However, as already mentioned in section 6, an application of SPOTTER on company-level is theoretically possible and particularly interesting for companies affected by the "Corporate Sustainability Reporting Directive" (European Commission 2022a) or the German "Lieferkettengesetz" (Federal Ministry of Labour and Social Affairs 2021). To overcome potential data gaps due to data access and confidentiality issues, assessments on a company-level should be performed in collaboration with interested organizations.

Application to additional sectors/countries. While supply chains within the mobility, energy and ICT sectors in Switzerland have been analyzed with SPOTTER, the supply chains within other sectors may also be affected by supply disruptions as shown by recent events. For example, the COVID-19 pandemic, recent natural disasters and the Russian-Ukrainian conflict have led to disruptions in the supply chains within the healthcare, food and textile sectors (Jagtap et al. 2022; Kumar et al. 2020; Reddy et al. 2016). To address the issue of limited sector coverage, additional case studies focusing on other relevant sectors of the Swiss economy could be performed with SPOTTER. Finally, the case studies performed within this dissertation have focused on the supply chains of the Swiss economy. In future case studies with SPOTTER, the supply disruption impacts along supply chains of other countries could be assessed and it could be analyzed whether different hotspots occur along these supply chains in comparison to the Swiss supply chains.

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Appendix A

Parts of Appendix A are based on the Supporting Information of Berr et al. (2022) and can be found online (https://doi.org/10.1016/j.clscn.2022.100063).

A.1 Overview of reviewed criticality assessment approaches

Table A1: Overview of pioneering criticality assessment approaches
including the description of the organizational level, the geography, the time horizon, the objectives, the supply disruption event and the indicators for supply disruption events (EIs) considered in the NRC, Yale, EC and NEDO criticality assessment approaches

Author	Organizational level	Geography	Time scale	Objectives	Supply disruption event	EIs
National Research Council (NRC) **(NRC 2008)**	Economy	USA	<10 years	Development of criticality assessment methodology (the 'criticality matrix'), which highlights the supply disruption probability and importance of critical minerals used in the automotive, aerospace, electronics and energy sectors	Depletion of economic resources	Ratio of stock of abiotic economic resources (called reserves by NRC (2008)) to global annual production over depletion duration
					Depletion of ultimate resources	Ratio of stock of abiotic ultimate resources (called reserve base by NRC (2008)) to global annual production over depletion duration
					Co-product dependency	Percentage of global production as co-product
					Primary raw material reliance	Percentage of national secondary raw material content in the national produced product
					Import dependency	Net imports to apparent consumption ratio

Table A1 (continued)

Author	Organizational level	Geography	Time scale	Objectives	Supply disruption event	EIs
Yale University (Yale) (Graedel et al. 2012)	Future generations	Global	Few decades	Development of a criticality assessment methodology for metals to support future policy developments of corporations and governments	Depletion of ultimate resources	Depletion time of ultimate resources (called reserve base by Graedel et al. (2012)) (see calculation in Supporting Information of Graedel et al. (2012))
					Co-product dependency	Percentage of global production as co-product
	Economy	N/A applied to the US	5-10 years	Development of a criticality assessment methodology for metals to support policy developments of governments	Depletion of economic resources	Depletion time of economic resources (called reserves by Graedel et al. (2012)) (see calculation in Supporting Information of Graedel et al. (2012))
					Co-product dependency	Percentage of global production as co-product
					Geopolitical instability	100 minus Worldwide Governance Indicator (Political Stability & Absence of Violence/Terrorism) (WGI(PV))
					Social regulations	Policy Perception Index (PPI)
						Human Development Index (HDI)
					Production concentration	Herfindahl-Hirschman Index (HHI)

Table A1 (continued)

Author	Organizational level	Geography	Time scale	Objectives	Supply disruption event	EIs
Yale University (Yale) (Graedel et al. 2012)	Company	N/A	1-5 years	Development of a criticality assessment methodology for metals to support policy developments of corporations	Depletion of economic resources	Depletion time of economic resources (called reserves by Graedel et al. (2012)) (see calculation in Supporting Information of Graedel et al. (2012))
					Co-product dependency	Percentage of global production as co-product
					Geopolitical instability	100 minus Worldwide Governance Indicator (Political Stability & Absence of Violence/Terrorism score)
					Social regulations	Policy Perception Index (PPI)
						Human Development Index (HDI)
					Production concentration	Herfindahl-Hirschman Index (HHI)
European Commission (EC) (European Commission 2017a)	Economy	EU	10 years	Assessment to identify critical raw materials for the EU. Revision of the criticality assessment methodology from the years 2010 and 2014	Geopolitical instability	Worldwide Governance Indicators (WGIs)
					Primary raw material reliance	1 minus the percentage of national secondary raw material content of the national production amount
					Substitutability	Depletion potential, criticality and co-product dependency of substitute
					Trade barriers	Value for export taxes/trade agreements
					Import dependency	Net imports to apparent consumption ratio

Table A1 (continued)

Author	Organizational level	Geography	Time scale	Objectives	Supply disruption event	EIs
New Energy and Industrial Technology Development Organization (NEDO) (Hatayama and Tahara 2015)	Economy	Japan	1-5 years	Presentation of Japan's criticality, support for the development of Japan's resource strategy and identification of the need for substitutes	Depletion of economic resources	Global economic resources (called reserves by Hatayama and Tahara (2015)) to production ratio
					Limited recyclability	Value for recycling opportunities
					Price increase	Ratio of price in the past to current price
					Price volatility	Ratio of highest to lowest price throughout 10 years
					Production growth	Ratio of current annual production to annual production 10 years in the past
					Demand growth	Ratio of current annual demand to annual demand 10 years in the past
					Stockpiles	Stockpile covering a 60-day demand
					Restriction on usage	Value for ecotoxicity of metals
					Resource concentration	Reserve share of the country holding globally the highest resource amounts
					Production concentration	Production share of the country producing globally the highest amounts
					Market concentration	Import share of the country importing the highest amounts into the consumer country

A.2 Justification of indicator selection conditions

Ten conditions have been defined in Table 5 regarding the identification of indicators for supply disruption events (EIs) suitable for a consideration in the SPOTTER approach. Justifications and explanation for each of these conditions are provided in the following paragraphs.

Condition (1): "Does the EI represent supply disruption events that are analyzed by at least 10% of the criticality assessment approaches reviewed by Schrijvers et al. (2020b) (see indicators for supply disruption probability listed in Figure 8)?"

Analyzing all possible supply disruption events requires enormous efforts in data acquisition and impact score calculation or may even not be feasible in some cases due to missing indicators. In order to reduce the computational and data acquisition effort during the assessment and ensure the feasibility of the evaluation, the SPOTTER approach prioritizes EIs that represent supply disruption events commonly analyzed within existing criticality assessment approaches. Another reason for considering these commonly analyzed events refers to their relevance for assessments of potential supply disruption impacts. While it is generally uncertain which events will lead to supply disruptions in the future, the combined knowledge of experts in the field of criticality assessment on event selection is supposedly one of the best sources to identify relevant supply disruption events. This knowledge is reflected by the collection of the most commonly analyzed events. In our study, these events are considered as the ones that are analyzed by at least 10% of the approaches reviewed by Schrijvers et al. (2020b). An overview of indicators related to these events is provided in Figure 8.

Condition (2): "Does the EI refer to an aspect of supply disruption risk that has not already been described with another indicator included in the calculations?"

Results are distorted when a specific aspect of supply disruption risk is unintentionally considered with a higher contribution on the impact than other analyzed risk aspects. In order to avoid the double counting of impact contributions of specific risk aspects, EIs are selected that do not refer to risk aspects already described with another included indicator. For example, the Herfindahl-Hirschman Index (HHI), which refers to the risk of concentrated production, is used as an EI in the approach developed by Bach et al. (2016), but is also used as an indicator for supplier diversity (DI) in the approach developed by European Commission (2017a). In order to avoid the double counting of the contribution of this aspect on the impact, the related indicator is included as EI *or* DI.

Condition (3): "Does the EI represent an event relevant for a short-term (ST) or medium-term (MT) assessment?"

SPOTTER evaluates the supply disruption impacts over two specific time horizons, i.e. the ST and the MT. In order to address the two time horizons, EIs are selected that represent supply disruption events relevant for either ST or MT assessments. EIs are evaluated as unsuitable when they only represent events relevant for assessments over another time horizon such as the long-term (i.e. several decades).

Condition (4): "Does the EI refer to only one specific causation of the supply disruption event?"

For the interpretation of results for supply disruption impacts and the implementation of possible risk mitigation measures, it is beneficial to be able to easily identify the origin of the supply disruption. In order to ease the identification of this origin, EIs are selected that refer to only one specific causation of the supply disruption event. Here, EIs are evaluated as unsuitable that refer to several causations of a supply disruption event. An example of such an unsuitable EI is the overall Worldwide Governance Indicator (WGI) developed by the World Bank, which is used by Bach et al. (2016) to represent the event of geopolitical instability. This indicator refers to six different causations of geopolitical stability, including voice and accountability, political stability and absence of violence/terrorism, government effectiveness, regulatory quality, rule of law and control of corruption (World Bank 2019).

Condition (5): "Is the analysis of the supply disruption event independent of the type of material/product? If not, does the EI, in comparison to other indicators for the same event, allow for the broadest coverage of materials/products?"

Burden shifting between impacts at different places in the supply chain needs to be avoided, when choices regarding a more resilient supply chain design are made. In order to avoid burden shifting between the impacts of different materials and products, EIs are selected that allow for assessing impacts of all materials/products used within the supply chain. For example, in case of EIs for social regulations such as the restrictions of child labor, EIs are selected that cover all materials and products in order to avoid the burden shifting to the supply of a material/product, which is associated with high child labor risk. Some EIs are however independent of the type of traded material/product and thus do not need to be evaluated according to this condition. This is the case for EIs representing for example geopolitical instability because the evaluation of the geopolitical situation does not depend on the considered material or product.

Condition (6): "Does the EI allow for the assessment of biotic and abiotic resources?"

In order to avoid the burden shifting between supply disruption impacts of different types of resources, i.e. biotic and abiotic resources, EIs are selected that allow for assessing impacts of both resource types.

Condition (7): "In case of country-specific events, does the EI provide the broadest coverage of countries in comparison to other indicators for the same event?"

In order to avoid burden shifting between impacts stemming from events that occur in different countries, EIs are selected that provide, in comparison to other indicators for the same event, indicator values related to the most countries worldwide.

Condition (8): "Can publicly available data be used to quantify the EI?"

An assessment is applicable when its related data are freely accessible and the transparency of an assessment is higher when its results are possible to be reproduced. It is thus important to select EIs that can be quantified by using publicly available data, as this ensures a sufficient data availability and the possibility to reproduce the results. For example, EIs quantified based on company-specific information are not considered in the SPOTTER approach because confidential corporate data may often not be publicly accessible. Furthermore, EIs evaluated based on expert or author judgement are not considered for an assessment with the SPOTTER approach because these judgments may reflect the bias of experts or authors.

Condition (9): "Is it possible to adjust EI values with different future scenarios for MT assessments?"

Future scenarios are increasingly used in Life Cycle Assessment (LCA)-based approaches to provide sustainability assessments of emerging products, technologies and systems (Bisinella et al. 2021). As stated in section 3.3, future scenarios are also to be considered for the MT assessments with the SPOTTER approach. In order to allow for MT assessments based on future scenarios, EIs are selected, of which the values are adjustable with different future scenarios. A suitable EI is, for example, the indicator for demand growth that is defined by the future demand modelled in the scenarios. Conversely, an unsuitable EI is, for example, the indicator for demand growth that is defined by past production amounts because these production amounts cannot be adjusted with different future scenarios.

Condition (10): Do higher values of the EI describe higher impacts?

The SPOTTER approach considers that higher indicator values describe higher impact scores in order to allow for a consistent interpretation of results. Following the ESP approach (Schneider et al. 2013), the order is inverted, in a way that higher indicator values corresponds to a higher risk, when needed. An example is the WGI - Political Stability and Absence of Violence/Terrorism, which describes the highest possible probability of political stability with a score of 100 and the lowest possible probability with a score of 0 (World Bank 2019). In order to indicate a higher impact with a higher indicator score, the values of this WGI are subtracted from 100.

A.3 Evaluation of indicator suitability

All EIs collected from the four criticality assessment approaches reviewed in the Appendix A.1 undergo the two evaluation steps, which are described in Figure 12.

A.3.1 First evaluation step

A first evaluation step is performed to identify the EIs suitable to represent the scope of supply disruption events that the SPOTTER approach considers. In this first step, the collected EIs are compared against the conditions (1) to (3) listed in Table 5 and described in Appendix A.2. After their evaluation, the EIs are divided into suitable and unsuitable EIs. The unsuitable EIs, i.e. the EIs that do not fulfill the three conditions, are listed in Table A2, while the suitable EIs are again considered for the evaluation described in Appendix A.3.2.

Table A2: List of indicators excluded during the first evaluation step.
The approaches from which the EIs have been collected are stated in brackets.

Represented supply disruption event	Unsuitable EIs (Approach)
Condition 1: Does the EI represent supply disruption events that are analyzed by at least 10% of the criticality assessment approaches reviewed by Schrijvers et al. (2020b) (see indicators for supply disruption probability listed in Figure 8)?	
Price increase	Ratio of price in the past to current price (Hatayama and Tahara 2015)
Stockpile	Stockpile covering a 60-day demand (Hatayama and Tahara 2015)
Potential usage restrictions	Value for ecotoxicity of metals (Hatayama and Tahara 2015)

Table A2 (continued)

Represented supply disruption event	Unsuitable EIs (Approach)
Condition 2: Does the EI refer to an aspect of supply disruption risk that has not already been described with another indicator included in the calculations?	
Substitutability	Substitute depletion, criticality and by-product dependency (European Commission 2017a)
Import dependency	Net imports to apparent consumption ratio (European Commission 2017a; NRC 2008)
Production concentration	Herfindahl Hirschman Index (Graedel et al. 2012)
Production concentration	Production share of the country producing globally the highest amounts (Hatayama and Tahara 2015)
Resource concentration	Resource share of the country holding globally the highest resource amounts (Hatayama and Tahara 2015)
Market concentration	Import share of the country importing the highest amounts into the consumer country (Hatayama and Tahara 2015)
Production growth	Ratio of current annual production to annual production 10 years in the past (Hatayama and Tahara 2015)
Condition 3: Does the EI represent an event relevant for a ST or MT assessment (see distribution of indicators into time horizons described in Figure 8)?	
-	-

Considering the first condition, all EIs are evaluated as unsuitable that do not represent supply disruption events, which are analyzed by at least 10% of the criticality assessment approaches reviewed by Schrijvers et al. (2020b). An overview of indicators related to these events is given by the list of indicators for supply disruption probability presented in Figure 8. Because the events of price increase, stockpile and potential usage restrictions do not belong to these most frequently analyzed events, the related EIs are excluded from the impact assessment within the SPOTTER approach.

Considering the second condition, all EIs are evaluated as unsuitable that address an aspect of a supply disruption risk, which is already represented by another indicator included in the SPOTTER approach. An EI, which is therefore excluded from the impact assessment within the SPOTTER approach, is the indicator of substitute criticality. This EI represents the risk of limited substitution opportunities for raw materials, which is already considered in the vulnerability evaluation of the SPOTTER approach (see section 3.2.3). The substitutability indicators have been used for the evaluation of vulnerability instead of supply disruption probability because substitutability is, according to Schrijvers et al. (2020b), more often analyzed as part of the vulnerability evaluation in existing criticality assessment approaches. Furthermore, the indicators of import dependency, resource concentration, production concentration and market concentration are rated as unsuitable, because indicators for supplier diversity (DIs) already reflect the risk associated with these dependencies and concentrations. Finally, the indicator of production growth is rated as unsuitable. Considering that production development usually follows the same trend as the development of demand, the risk related to production growth is reflected by an analysis of demand growth. Demand growth has been prioritized as it is, according to Schrijvers et al. (2020b), more frequently considered in criticality assessment approaches than production growth.

Considering the third condition, all EIs are evaluated as unsuitable that do not represent an event that is relevant for the short- or medium-term assessments. As shown in Figure 8, analyzed events are relevant for short- or medium-term assessment or assessments over both time horizons. Thus, none of the collected EIs has been identified as unsuitable.

A.3.2 Second evaluation step

The EIs that are suitable to represent the scope of events considered in the SPOTTER approach undergo the second evaluation step. In this step, the EIs are compared against the conditions (4) to (10) listed in Table 5 and explained in Appendix A.2. EIs are thus identified that do not comply with the requirements for assessing the different impacts covered with the SPOTTER approach. After evaluating the EIs, the suitable EIs and the EIs, which are unsuitable and need to be replaced with other EIs, are identified. The latter category of EIs and their possible replacement options are described in Table A3. A list and description of all suitable EIs are provided in Appendix A.5.

Table A3: List of indicators excluded during the second evaluation step
comprising the indicators for supply disruption events (EIs) that are rated as unsuitable and descriptions of possible replacement options for each of the unsuitable EIs. The approaches, from which the EIs have been collected, are stated in brackets.

Supply disruption event	EIs identified as unsuitable (Approach)	Replacement option in form of another initially/additionally collected EI (Approach)	Does the replacement option comply with all conditions?
Condition 4: Does the EI refer to only one specific causation of the supply disruption event?			
Depletion of economic/ ultimate resources	**Depletion time of economic/ultimate resources (Graedel et al. 2012)**	Ratio of stock of economic/ultimate abiotic resources to global annual production over the depletion duration (NRC 2008)	No, conditions (6), (7) and (10) are unfulfilled.
Geopolitical instability	**Worldwide Governance Indicators**	100 minus Worldwide Governance Indicator (Political Stability & Absence of Violence/Terrorism) (WGI(PV)) (Graedel et al. 2012)	Yes
Condition 5: Is the analysis of the supply disruption event independent of the type of material/product? If not, does the EI, in comparison to other indicators for the same event, allow for the broadest coverage of materials/products?			
Social regulations	**Policy Perception Index (PPI) (Graedel et al. 2012)**	Risk of child labor by sector (Benoit Norris et al. 2019)	Yes
	Human Development Index (HDI) (Graedel et al. 2012)		
Condition 6: Does the EI allow for the assessment of biotic and abiotic resources?			
Depletion of economic/ ultimate resources	**Ratio of stock of abiotic economic/ultimate resources to global production over depletion duration (NRC 2008)**	Ratio of stock of economic/ultimate abiotic or biotic resources to global annual production minus the replenishment rate over depletion duration (adapted from Bach et al. (2017a))	No, conditions (7) and (10) are unfulfilled.
Condition 7: In case of country-specific events, does the EI provide the broadest coverage of countries in comparison to other indicators for the same event?			
Trade barriers	**Value for export taxes/trade agreements (European Commission 2017a)**	Trading Across Borders Indicator (World Bank 2020)	No, condition (10) is unfulfilled.
Depletion of economic/ ultimate resources	**Ratio of stock of economic/ultimate abiotic or biotic resources to global annual production minus the replenishment rate over depletion duration**	Ratio of stock of economic/ultimate abiotic or biotic resources to national annual production minus the replenishment rate over depletion duration (own modification)	No, conditions (9) and (10) are unfulfilled.

Table A3 (continued)

Supply disruption event	EIs identified as unsuitable (Approach)	Replacement option in form of another initially/additionally collected EI (Approach)	Does the replacement option comply with all conditions?
Condition 8: Can publicly available data be used to quantify the EI?			
Limited recyclability	**Value for recycling opportunities (Hatayama and Tahara 2015)**	End-of-Life recycling rate (EOL-RR) of the raw material (Tuma et al. 2014)	No, condition (10) is unfulfilled.
Condition 9: Is it possible to adjust EI values with different future scenarios for MT assessments?			
Demand growth	**Ratio of current annual demand to annual demand 10 years in the past (Hatayama and Tahara 2015)**	Ratio of annual global future demand in 10 years to global current production (adapted from Angerer et al. (2009))	Yes
Primary raw material reliance	**1 minus the percentage of national secondary raw material content of the national production amount (European Commission 2017a)**	1 minus the percentage of global secondary future raw material content of the global future production amount	Yes
Depletion of ultimate resources	**Ratio of stock of ultimate abiotic or biotic resources to national annual production minus the replenishment rate over depletion duration**	Ratio of stock of ultimate abiotic or biotic resources to national annual future production minus the replenishment rate over depletion duration (own modification)	No, condition (10) is unfulfilled.
Condition 10: Do higher values of the EI describe higher impact scores?			
Trade barriers	**Trading Across Borders Indicator (World Bank 2020)**	100 minus Trading Across Borders Indicator (own modification)	Yes
Limited recyclability	**End-of-Life recycling rate EOL-RR of the raw material (Tuma et al. 2014)**	1 minus End-of-Life recycling rate (EOL-RR) of the raw material (own modification)	Yes
Depletion of economic resources	**Ratio of stock of economic abiotic or biotic resources to national annual production minus the replenishment rate over depletion duration**	Ratio of national annual production minus the replenishment rate to the national stocks of economic abiotic or biotic resources (own modification)	Yes
Depletion of ultimate resources	**Ratio of stock of ultimate abiotic or biotic resources to national annual future production minus the replenishment rate over depletion duration**	Ratio of national annual future production minus the replenishment rate over depletion duration to the national stocks of ultimate abiotic or biotic resources (own modification)	Yes

Considering the fourth condition, EIs are identified that refer to only one specific causation of a supply disruption event. The EI *depletion time of economic or ultimate resources* used by Graedel et al. (2012) is identified as unsuitable. This indicator covers, additionally to the difference between the resource stock and the extraction rate over a certain period, the End-of-Life (EoL) recycling rate and the loss during the product life cycle. It thus becomes difficult to identify whether the depletion originates from high extraction rates, low stocks, high losses or low EoL recycling rates. This EI is replaced with the EI *ratio of stock of economic/ultimate abiotic resources to global annual production over depletion duration*, collected from (NRC 2008), which allows clear identification of whether the supply disruption event originates from high extraction rates and low stocks. Furthermore, the EI *Worldwide Governance Indicators (WGIs)*, collected from the EC approach, is rated as unsuitable, since it combines six different sub-indicators, of which each represents a different causation of poor governance (World Bank 2019). As a replacement, the EI *100 minus Worldwide Governance Indicator (Political Stability & Absence of Violence/Terrorism) (WGI(PV))* collected from the Yale approach is chosen, because it refers to only one specific causation of geopolitical instability.

Considering the fifth condition, EIs are identified that allow for the relatively broadest coverage of materials and products. Two EIs representing the event of social regulations, the *Policy Perception Index (PPI)* and the *Human Development Index (HDI)*, which are both collected from the Yale approach, are identified as unsuitable. The *PPI* is limited to an assessment of minerals but does not cover other kinds of materials or products. The *HDI* does not provide results specific to certain materials/products but only one aggregated result for any kind of material or product. The EI *risk of child labor by sector*, collected from Benoit Norris et al. (2019), is used as a replacement for both EIs. It provides, among the identified EIs representing social regulations, the relatively broadest coverage of values specific to certain material/product groups[16] (Benoit Norris et al. 2019). The EIs representing geopolitical instability do not need to be evaluated according to the fifth condition, since the evaluation of the geopolitical situation is independent of the supplied material or product. Furthermore, the EIs representing trade barriers are also not evaluated according to the fifth condition, since suitable kinds of these EIs found in the literature do not allow for addressing potential trade restrictions specific to materials or products.

Considering the sixth condition, EIs that allow for the assessment of biotic and abiotic resources are identified. EIs representing depletion of economic/ultimate resources currently only cover abiotic resources and thus need to be adjusted in order to fulfill this condition. Following the suggestion within the BIRD method (Bach et al. 2017a), the replenishment rate is additionally considered to allow for coverage of biotic resources.

Considering the seventh condition, EIs with the comparably broadest coverage of countries are identified. Only EIs representing country-specific supply disruption events are evaluated according to

[16] The represented material/product groups are defined based on 57 economic sectors included in the Global Trade Analysis Project (GTAP) model (Benoit Norris et al. 2019).

this condition. The EI *value for export taxes/trade agreements* collected from the EC approach describes the probability of trade barriers between the EU countries and the non-EU countries only. This EI is replaced with the EI *Trading Across Borders Indicator (TABI)*, collected from the World Bank (2020) because the *TABI* allows for a broad country coverage regarding an analysis of trade barriers (coverage of 190 different countries). Furthermore, the EIs representing the depletion of economic/ultimate resources are adjusted in order to allow for analysis on a national instead of a global level. Production amounts and resource stocks are thus considered from a country-specific instead of a global perspective.

Considering the eighth condition, EIs are identified that can be quantified using publicly available data. The EI *value for recycling opportunities* representing limited recyclability is rated as unsuitable since it is evaluated based on the judgment of authors of the NEDO approach. This EI is replaced with the *EoL-recycling rate of the raw material* collected from Tuma et al. (2014), for which data are publicly reported by for example Coughlan and Fitzpatrick (2020).

Considering the ninth condition, EIs, of which the values can be adjusted with different future scenarios, are identified. Future scenarios are only used for the definition of EIs relevant for the medium-term assessment and thus only this type of EIs are evaluated according to the condition. Three EIs are rated as unsuitable in this context and need adaptations. The first one is the EI *ratio of current annual demand to annual demand 10 years in the past*, collected from the NEDO approach. It only provides the possibility to create one future scenario based on production developments in the past but does not allow for the adjustments of its values with different future scenarios. This EI is thus replaced with the EI *ratio of annual global future demand in 10 years to global current production*, an EI developed based on the approach provided by Angerer et al. (2009). The second one is an EI that is collected from the EC approach and that represents the event of primary raw material reliance. To allow for an adjustment of the EI values with different future scenarios, raw material contents of the global future production amount instead of the current raw material contents are considered. The third one is the EI representing ultimate resource depletion. This EI is evaluated as unsuitable because measuring the current national extraction rates does not allow for considering future developments in ore production. Therefore, potential extraction rates in the future are considered instead of the current extraction rates.

Considering the tenth condition, EIs, of which higher values describe higher impacts, are identified. The four EIs: (i) *Trading Across Borders Indicator*, (ii) *EOL-recycling rates of raw materials*, (iii) *percentage of global secondary future raw material content of the global future production amount* and (iv) EIs representing the depletion of economic or ultimate resources need to be adapted in this regard. To comply with the condition, the values of the first three EIs are subtracted from 1 or 100. Concerning the fourth EI, a ratio between the production amount and the stock is used, which is adapted from the Abiotic Depletion Potential (ADP) indicator developed by van Oers et al. (2002).

A.4 Description of considered supply disruption events

The ten supply disruption events considered in the SPOTTER approach are described in Table A4. The descriptions of these events are adapted from explanations provided by Hatayama and Tahara (2018) and Jasiński et al. (2018).

Table A4: Descriptions of supply disruption events considered in the SPOTTER approach

Events	Description
Geopolitical instability	Restrictions in the production processes are caused by domestic conflicts and attacks through antisocial groups in politically unstable countries.
Child labor restrictions	Regulations concerning the avoidance of child labor interfere with production processes and their costs.
Trade barriers	Taxes or fees lead to increased prices for trade or insufficient flow of goods over borders.
Depletion of economic resources	The risk of a price increase is associated with the extraction of the required resources over the next few years.
Limited recyclability	Easily recyclable materials or products reduce the need for primary produced materials and the pressure on the underlying natural resources.
Price volatility	Volatile prices in the past lower the willingness of stakeholders to invest in a risky business.
Depletion of ultimate resources	The risk of a price increase is associated with the extraction of the required resources over the next decades.
Demand growth	Global demand growth of a technology describes potential pressure on production processes of required inputs.
Co-product dependency	The supply disruption is associated with materials/products that are produced as co-products. Usually, the main material/product justifies the production and the other materials/products are produced as companions. A decrease in the relevance of the production of the main material/product gets problematic for the production of the co-product.
Primary raw material reliance	The use of higher amounts of raw material produced from secondary production decreases the reliance on potentially unavailable primary produced raw materials and thus the pressure on the underlying natural resources.

A.5 Description of considered indicators for supply disruption events

Suitable EIs have been selected for each of the supply disruption events considered in the SPOTTER approach. Table A5 describes these EIs and additionally states the sources, from which the EIs have been collected or adapted.

Table A5: List and description of indicators for supply disruption events (EIs) considered in the SPOTTER approach. Additionally, the related event and the source, from which these EIs have been collected/adapted, are described.

Events	EIs	Description of EIs	Source
Geopolitical instability	**100 minus Worldwide Governance Indicator (Political Stability and Absence of Violence/Terrorism) (WGI(PV))**	The indicator "measures perceptions of the likelihood of political instability and/or politically motivated violence, including terrorism" (World Bank 2019). The WGI(PV) is measured in dimensionless units, with values ranging from 0 to 100, where 100 indicates the best political performance.	Yale approach (Graedel et al. 2012)
Child labor restrictions	**Risk of child labor by sector**	The indicator "refers to work for children under the age of 18 that is mentally, physically, socially and/or morally dangerous or harmful and interferes with their schooling" (Benoit Norris et al. 2019). The scaled indicator is measured in dimensionless units with values ranging from 0 to 1, where 1 indicates the highest risk of child labor.	(Benoit Norris et al. 2019)
Trade barriers	**100 minus Trading Across Borders Indicator**	"The data on trading across borders are gathered through a questionnaire administered to local freight forwarders, customs brokers, port authorities and traders" (World Bank 2020). The Trading Across Borders indicator is measured in dimensionless units with values ranging from 0 to 100, where 100 indicates the best trade performance of a country.	(World Bank 2020)

Table A5 (continued)

Events	EIs	Description of EIs	Source
Price volatility	**Ratio of highest to lowest annual price throughout three years**	$\frac{highest\ price\ over\ past\ 3\ years}{lowest\ price\ over\ past\ 3\ years}$ Prices can for example be defined based on trade databases, geological surveys or industry reports.	NEDO approach (Hatayama and Tahara 2015)
Limited recyclability	**1 minus End-of-Life recycling rate (EOL-RR) of the raw material**	$1 - End\ of\ life\ recycling\ rate$ End of life recycling rates are for example determined based on raw material recycling rates provided by journal articles, reports or websites.	(Tuma et al. 2014)
Depletion of economic resources	**Ratio of national annual production minus the replenishment rate to the national stocks of economic abiotic or biotic resources**	$\frac{national\ production\ - replenisment\ rate}{stock\ of\ national\ economic\ resources}$ The extraction rates and resource stocks can for example be determined based on geological surveys or resource-specific journal articles. The replenishment rate can for example be determined based on the average renewal time (in years/kg) over the considered period reported for different species by Crenna et al. (2018).	Bach et al. (2017a), van Oers et al. (2002)
Depletion of ultimate resources	**Ratio of national annual future production minus the replenishment rate to the national stocks of ultimate abiotic or biotic resources**	$\frac{national\ future\ production\ - future\ replenisment\ rate}{stock\ of\ national\ ultimate\ resources}$ Estimates for the future are made based on different scenarios, which are created by using for example technology roadmaps. When no other data on future replenishment rates is available, it is assumed that these rates are equal to the current replenishment rates.	Bach et al. (2017a), van Oers et al. (2002)

Table A5 (continued)

Events	EIs	Description of EIs	Source
Demand growth	**Ratio of annual global future demand in 10 years to global current production**	$\frac{global\ future\ demand\ in\ 10\ years}{global\ current\ production}$ Estimates for future demand are made based on different scenarios, which are created by consulting for example technology roadmaps. The current production is for example determined based on geological surveys or trade databases.	(Angerer et al. 2009)
Co-product dependency	**Percentage of global production as co-product**	$\frac{global\ current\ production\ as\ coproduct}{global\ current\ production}$ Information about the production as co-product is determined based on material/product-specific journal articles, reports or websites. Current production measures are considered because it is assumed that the production situations regarding co-products and main products do not vary significantly in the medium-term in comparison to today.	Yale approach (Graedel et al. 2012), NRC approach (NRC 2008)
Primary raw material reliance	**1 minus percentage of secondary future raw material content of the global future production amount**	$1 - ((global\ future\ secondary\ raw\ material\ content) / (global\ future\ primary\ raw\ material\ content + global\ future\ secondary\ raw\ material\ content))$ The content of secondary produced raw material can for example be determined based on future recycling scenarios.	EC approach (European Commission 2017a)

Appendix B

Parts of Appendix B corresponds to the Supporting Information of Berr et al. (2023) and can be found online (https://doi.org/10.1021/acs.est.3c05957).

B.1. Explanation of the considered bill of materials/products

As shown in Figure 15, different material/product inputs/outputs along the Co and Al supply chain of EVs are considered to describe the product system. The choices regarding the bill of materials are explained in this section.

Following Irle (2021), the considered EV types comprise BEVs and PHEVs. These two types of EVs have been selected because they offer the potential for carbon-free transport operations, which are important in terms of the decarbonization of the mobility sector (Hirschberg et al. 2016; Lattanzio 2020).

BEVs and PHEVs are typically equipped with a LIB that consists of a battery case and multiple battery cells. Each of these cells includes a cathode, an anode, a current collector, a circuit and an electrolyte (Castelvecchi 2021). Other components of the EVs are bodies, chassis, electric motors and electrical systems consisting of stranded wires (Egede 2017; Rajeev Kumar 2016). Following PrimecomTech (2019), AC or DC electric motors can be used for EVs. Following Schröder (2021) and Matt et al. (2021), DC electric motors with a power output between 750W and 375kW and AC electric motors with a power output between 10 kW and 100 kW are suitable for being used in EVs.

LIBs, bodies, chassis, electric motors and wiring of EVs are considered in the presented case study because they utilize Co and Al. The use of Co and Al in these EV components is explained in the next paragraph. Other EV components such as the internal combustion engine of PHEVs and the paint of EVs are neglected for the case study because Co and Al are usually not used for their production. Al alloys are typically not used in the internal combustion engines of the PHEVs, because, according to Sullivan et al. (2015), iron and steel are the preferred materials in these engines due to better noise suppression. While Al powder is sometimes used in the painting of the car, it is, according to International Driving Authority (2019), not a crucial constituent of the painting.

As mentioned before, the raw materials of Co and/or Al are part of the LIBs, bodies, chassis, electric motors and wiring of EVs. Cobalt powders and Al foils are usually used within the cathode of the LIB cells and alloyed Al plates are typically utilized within the cell housing and LIB cases (Castelvecchi 2021; Coffin and Horowitz 2018; Diekmann et al. 2016; Perner and Vetter 2015). Alloyed Al plates are furthermore applied in the frames of the bodies, chassis and electric motors of EVs (Liu et al. 2018; Rassõlkin et al. 2020; Tsirogiannis 2015). Al alloys are usually deployed in wires for the electrical system of EVs (Yu 2016).

As shown by Baars et al. (2021), the pure Co powder used in the LIBs of the EVs is produced through the extraction of Co ores from the Co resources stock as well as through processing of Co ores and Co intermediates. Following Schmidt et al. (2016), Co powder can be produced from three different types of Co intermediates, i.e. from Co mattes, from nickel-cobalt mattes or from nickel-cobalt sulfides. As illustrated by Liu and Muller (2013) and Liu et al. (2012), the production of unwrought Al used in the different EV components involves the extraction of bauxite resources as well as the processing of bauxite ores and Al oxides.

B.2. Identification of suitable data sources

In this section, two different databases are evaluated regarding their suitability to quantify the considered Co and Al supply chains. The first database is ecoinvent, the globally most detailed unit process life cycle inventory database (Wernet et al. 2016). The second database is BACI, a database reporting physical and monetary country-specific trade data for different material/product categories (Gaulier and Zignago 2010).

The two databases need to fulfill the following four criteria in order to be suitable for quantifying the considered supply chains:

i. availability of information for the technology type of relevant processes along the supply chain
ii. availability of information for inputs/outputs of the relevant materials/products
iii. availability of information for the relevant countries or geographical regions
iv. availability of up-to-date information

ecoinvent provides information for some specific processes along the supply chain (e.g. "cobalt production" with an output of Co powder), but information for other processes such as "processing of Co ore" or "production of BEVs" is missing. Material/product inputs and outputs are stated for each process that is included in ecoinvent. However, due to the lack of certain processes in the database, some of the relevant inputs/outputs are missing. Furthermore, geographical descriptions are often only available on a global level or for large regions (e.g. rest of the world) and thus, ecoinvent lacks sufficient country-specific information. Finally, some of the datasets are outdated (i.e. covering information that is older than 5 years). For example, at the time of our evaluation, a dataset for LIB cell production only exists for the year 2010, which is an issue especially with regard to fast developing technologies such as LIBs. In conclusion, ecoinvent is evaluated as unsuitable to be used for the quantification of the considered supply chain.

BACI covers trade data for more than 5'000 material/product categories related to 6-digit HS codes provided by the World Customs Organization (2021). The database receives annually updated bilateral trade flows for these categories from more than 200 countries. Based on these trade reports, BACI publishes physical trade amounts (measured in kg) and monetary trade values (measured in \$). To estimate the volume of trade when only monetary values are reported, a standard unit value is defined for each material/product category included in BACI. This standard unit value is calculated based on the median unit value of available ratios between monetary values and physical amounts (Reister and Muryawan 2019). Comparing the information in this database against the four criteria stated above, the datasets included in BACI that cover physical trade flows are seen as sufficient to be used for the quantification of the considered supply chains. The list of the HS codes that are thus considered for the presented case study is provided in Appendix B.3.

However, an issue concerning the aggregation levels of some of the relevant materials/products along the considered supply chains remains related to the datasets included in BACI. Trade amounts of Co mattes (approx. 27% Co content) and Co powder (approx. 100% Co content), which are actually produced by different processes along the supply chain, are covered within the same HS code, namely 810520 "Cobalt; mattes and other intermediate products of cobalt metallurgy, unwrought cobalt, powders" (Godoy León et al. 2021). Furthermore, trade amounts of LIB cells are covered together with cells of lead-acid batteries and nickel metal hydride batteries as well as other parts of electric accumulators such as containers and covers within the HS code 850790 "Electric accumulators; parts n.e.s. in heading no. 8507" (Coffin and Horowitz 2018; World Customs Organization 2021). Following the approach introduced by the European Commission (2017b), the trade data related to the individual materials/products within the two HS codes 850790 and 810520 have been identified by using cost-to-mass ratios. The adjustments related to the content of these two HS codes are explained in the Appendix B.4. The adjustments related to other HS codes considered for the case study (see list of HS codes in Appendix B.3) are explained in File 1 of the data repository D.1.

B.3. Considered Harmonized System (HS) codes

Table B1: Considered 6-digit Harmonized System (HS) codes related to the aluminium and cobalt supply chains of electric vehicles. Abbreviations: Cobalt (Co), Aluminium (Al), Lithium-ion battery (LIB), Electric vehicle (EV), Battery electric vehicle (BEV), Plug-in hybrid electric vehicle (PHEV)

Material/Product	HS codes	Description
Co intermediates (Co mattes, Nickel-cobalt mattes, Nickel-cobalt sulfides)	810520	Cobalt; mattes and other intermediate products of cobalt metallurgy, unwrought cobalt, powders
	750110	Nickel; nickel mattes
	750120	Nickel; oxide sinters and other intermediate products of nickel metallurgy
Al oxide	281820	Aluminium oxide; other than artificial corundum
Co powder	810520	Cobalt; mattes and other intermediate products of cobalt metallurgy, unwrought cobalt, powders
Al unwrought	760110 / 760120	Aluminium; unwrought, (not alloyed) / unwrought, alloys
Al foil	760719	Aluminium; foil
LIB cells	850790	Electric accumulators; parts
Al plate	760612 / 760692	Aluminium; plates, sheets and strip
Al wire	760521 / 760529	Aluminium; alloys, wire
LIB	850760	Electric accumulators; lithium-ion
EV body	870710	Vehicles; bodies for electric vehicles
EV chassis	870600	Chassis; fitted with engines, for the motor vehicles
Electric motors	850132 / 850133	Electric motors and generators; DC
	850152 / 850153	Electric motors; AC motors, multiphase
EV wiring	854430	Insulated electric conductors; wiring sets
BEV, PHEV	870380	Vehicles; with only electric motor for propulsion /
	870370 / 870360	Vehicles; with both compression-ignition or spark-ignition internal combustion piston engine and electric motor for propulsion, capable of being charged by plugging to external source of electric power

B.4. Adjustments related to the content of HS codes

Some of the considered 6-digit HS codes cover materials/products that are not only part of the supply chains of EVs but also part of the supply chains of other products. Information provided by the World Customs Organization (2021) has thus been used to identify the type of materials and products that are covered within the respective HS codes. If materials/products that are not part of the Co or Al supply chains of EVs are covered within a certain HS code, the content of this HS code has been adjusted. These adjustments have been done based on global average market shares and global average cost-to-mass ratios. To simplify the procedure of adjusting the HS codes content, considered market shares are generally applied to both, the trade amounts and the trade costs of materials/products. It is thus assumed that materials/products covered within the same HS code generally have equal cost-to-mass ratios. If relevant materials/products associated with different cost-to-mass ratios are covered within the same HS code, their respective cost-to-mass ratios are estimated and considered for the adjustment of the HS code content.

Following, the adjustments related to the contents of HS codes are explained by the example of the HS codes 850790 and 810520 that are used for the analysis of Co and Al supply chains of EVs. All adjustments related to the content of HS codes performed in the frame of the presented case study are described in File 1 of the data repository D.1.

Adjustments related to the content of the HS code 850790: The HS code 850790 covers battery modules as well as battery cells that are used in different types of batteries, including cells of LIBs, lead acid batteries (PbAcBs), nickel-metal hydride batteries (NMHBs) and other batteries. These batteries are applied in the electromobility, stationary and electronics sectors. A share of 60% of these batteries is included in the electromobility sector according to the U.S. Department of Energy (2020), Tsiropoulos et al. (2018) and Grand View Research (2019). According to Grand View Research (2019), the shares of PbAcBs, NMHBs and other batteries in the electromobility sector are 30%, 5% and 5%. These market shares in combination with cost-to-mass ratios of the different battery cells are used to identify the trade amounts and costs of LIB cells. These ratios are calculated based on the energy densities reported by Wong and Chan (2012) (i.e. LIBs: 0.16kWh/kg, PbAcBs: 0.035kWh/kg, NMHB: 0.07kWh/kg) and the cost-to-energy ratios reported by Mongird et al. (2019) (i.e. LIB: 271$/kWh, PbAcBs: 260$/kWh, NMHB: 600$/kWh). Following BloombergNEF (2020), it is assumed that the prices of battery packs are 70% of the prices of battery cells. The resulting cost-to-mass ratios are 6 $/kg for PbAcB cells, 29 $/kg for NMHB cells and 30 $/kg for LIB cells. Thus, the following three requirements are considered: (i) all trades with a cost-to-mass ratio below or equal to 6$/kg are assumed to be PbAcB cells or battery cases, (ii) all trades with a cost-to-mass ratio between 6$/kg and 30$/kg are assumed to be 60% LIB cells, 30% PbAcB cells, 5% NMHB cells and 5% other battery cells and (iii) all trades with a cost-to-mass ratio above or equal to 30$/kg are assumed to be 90% LIB cells and 10% NMHB or other battery cells.

Adjustments related to the content of the HS code 810520: The HS code 810520 covers Co powder, which is used in different types of applications, and comprises Co matte, which is an intermediate product from the production of cobalt powder. As stated in the previous paragraph, it is estimated that 60% of all LIBs containing Co are used in the electromobility sector. According to Petavratzi et al. (2019), 61% of the Co materials that are covered by the HS code are Co powder used in LIBs. Here, it is assumed that the HS code includes Co powder used in batteries, superalloys, hard metals and magnets but not cobalt chlorides and oxides used in pigments, organics, etc. (see HS codes 282200 and 282734). Cost-to-mass ratios of Co powder and mattes are used to identify the trade amounts and costs of Co powder. These ratios are defined based on the average market price of cobalt metal (i.e. 26$/kg on 29. July 2019 according to London Metal Exchange (2021) and Trading Economics (2021)) and based on the average market price of Co mattes (i.e. 11$/kg according to Baars et al. (2021) and the European Commission (2020c)). Thus, the following three requirements are considered: (i) all trades with a cost-to-mass ratio below or equal to 11$/kg are assumed to be Co mattes, (ii) following Baars et al. (2021), all trades with a cost-to-mass ratio between 11$/kg and 26$/kg are assumed to be 50% Co mattes and 50% Co powder and (iii) all trades with a cost-to-mass ratio above or equal to 26$/kg are assumed to be cobalt powder.

B.5. Procedure for supply chain quantification

Figure B1 illustrates the procedure for the quantification of the Co and Al supply chain of EVs used in Switzerland. Here, additionally to the explanations in Figure 16, the quantification of inventory flows of four additional unit processes upstream of supply chain is described. The steps 8 to 11 and all further steps are performed analogously to the steps 4 to 7 described in section 4.1.3.

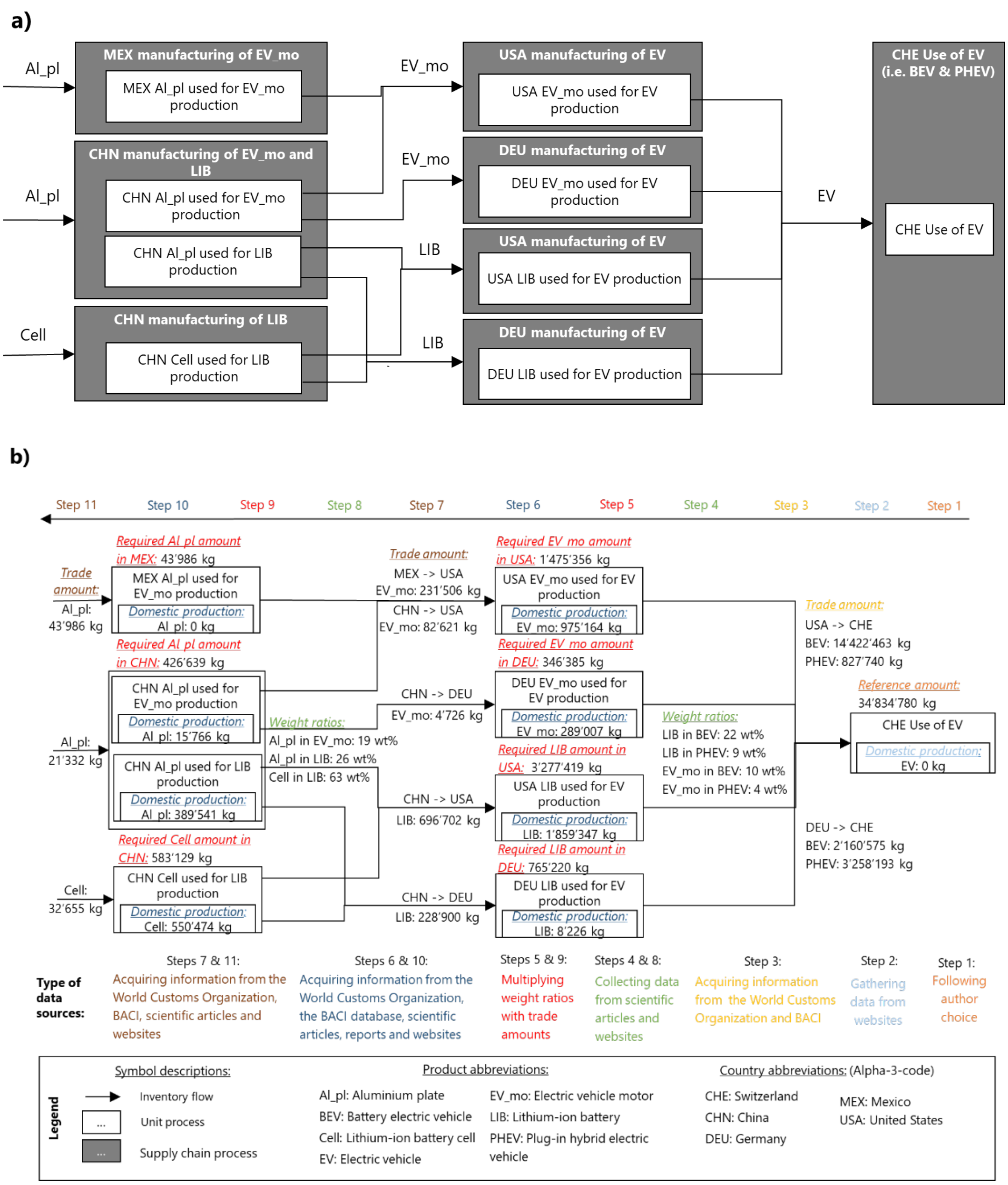

Figure B1: Extended illustration of the procedure used to quantify the supply chain including (a) the description of unit processes for a part of the cobalt and aluminium supply chain of electric vehicles used in Switzerland in the year 2019 and (b) the exemplary quantification of this part of the supply chain. The quantification procedure is illustrated for four additional unit processes upstream of the processes presented in Figure 16.

B.6. Hotspot contribution analysis

The results of the hotspot contribution analysis are presented for the individual material/product flows on the level of the impact category (Figure B2) and on the level of the impact category and supply disruption event (Figure B3).

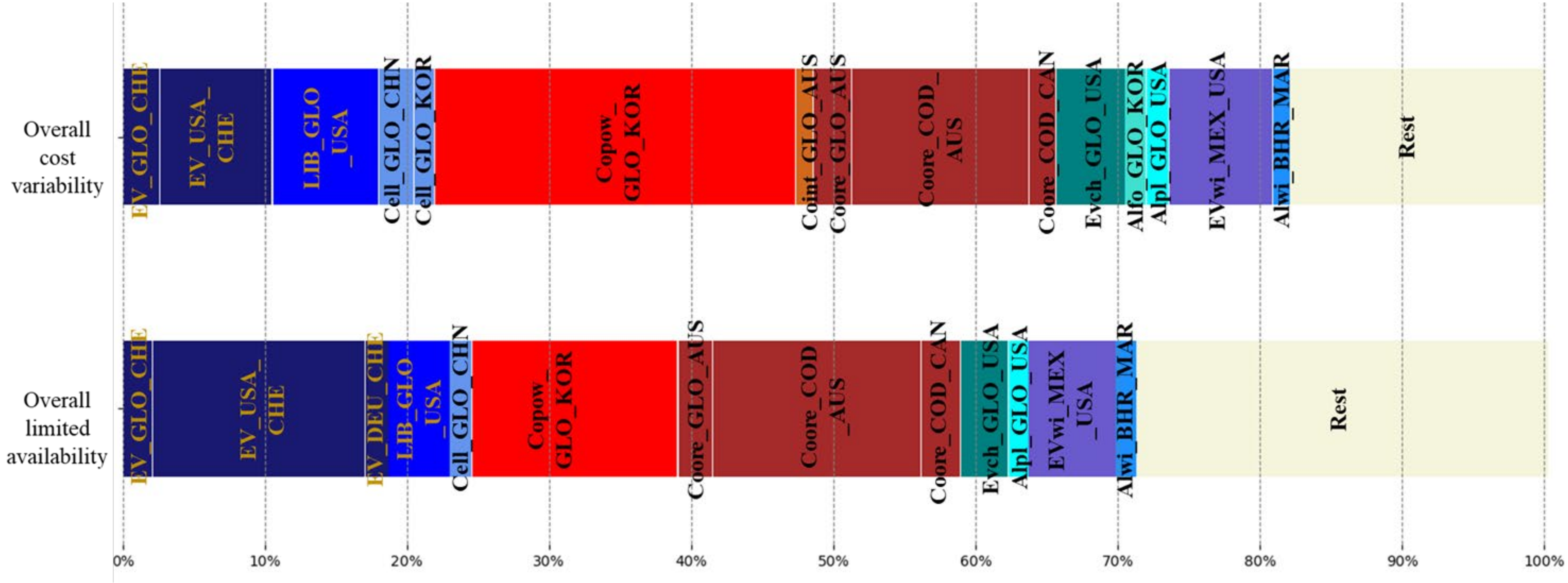

Figure B2: Magnitude of hotspots per impact category
considering cost variability and limited availability related to material/product flows. Abbreviations for the materials/products are explained in Figure 18 and abbreviations for countries are based on alpha-3 codes (GLO refers to flows originating from the global market).

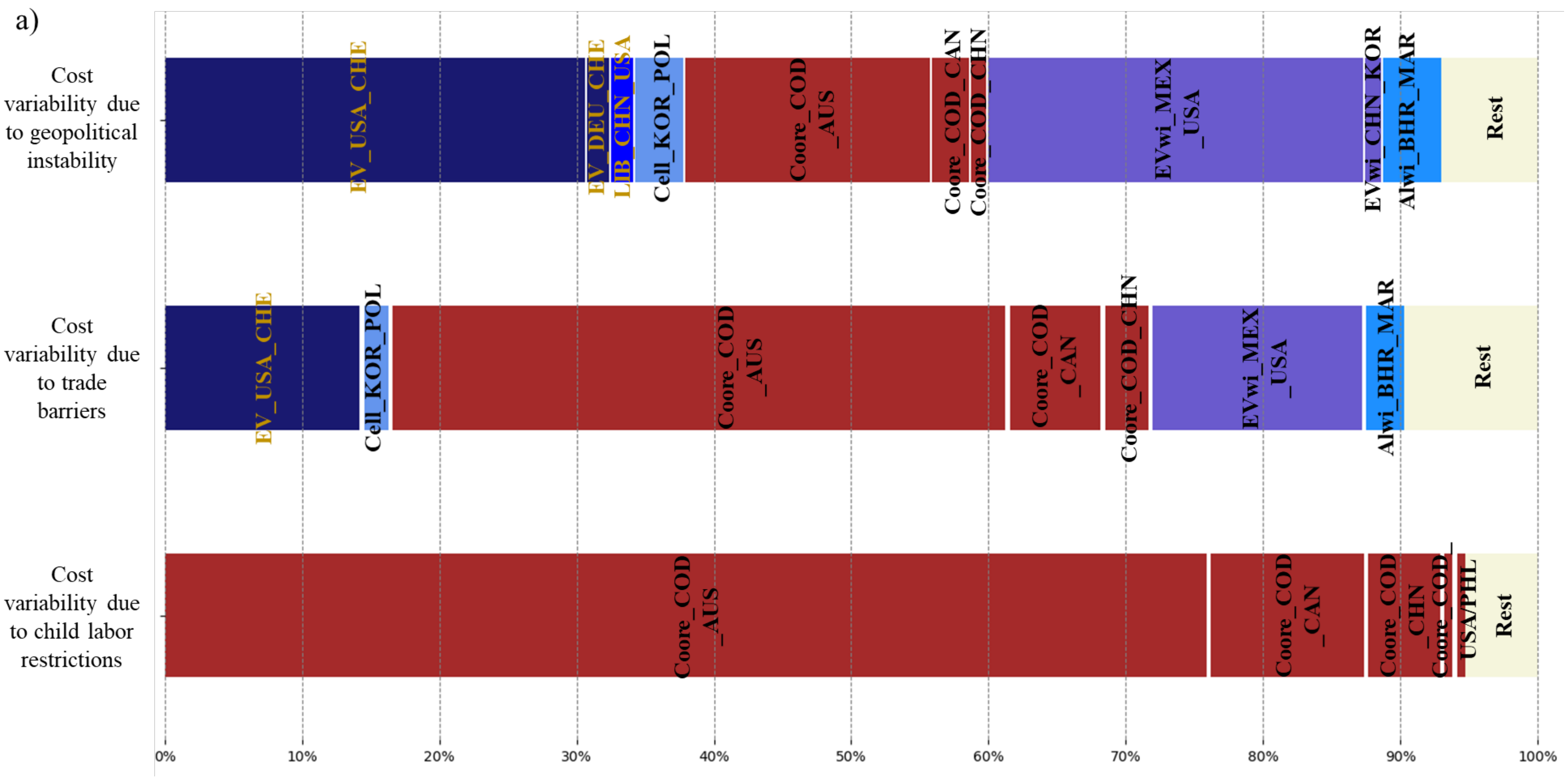

Figure B3: Magnitude of hotspots per event and impact category considering a) cost variability and b) limited availability caused by geopolitical instability, trade barriers and child labor restrictions as well as c) cost variability and d) limited availability caused by price volatility, limited recyclability and economic resource depletion. Abbreviations for the materials/products are explained in Figure 20 and abbreviations for countries are based on alpha-3 codes (GLO refers to flows originating from the global market).

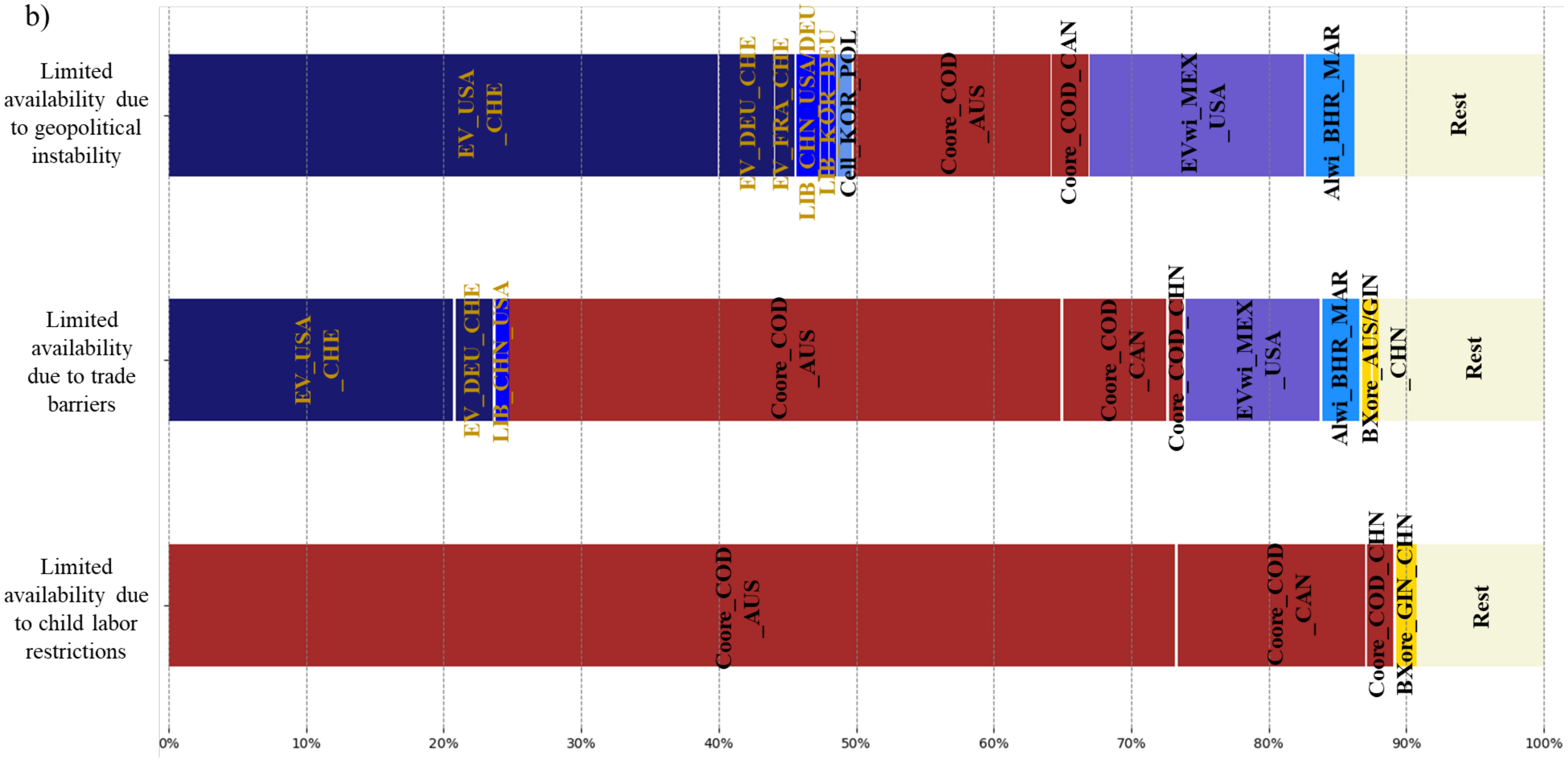

Figure B3 (continued)

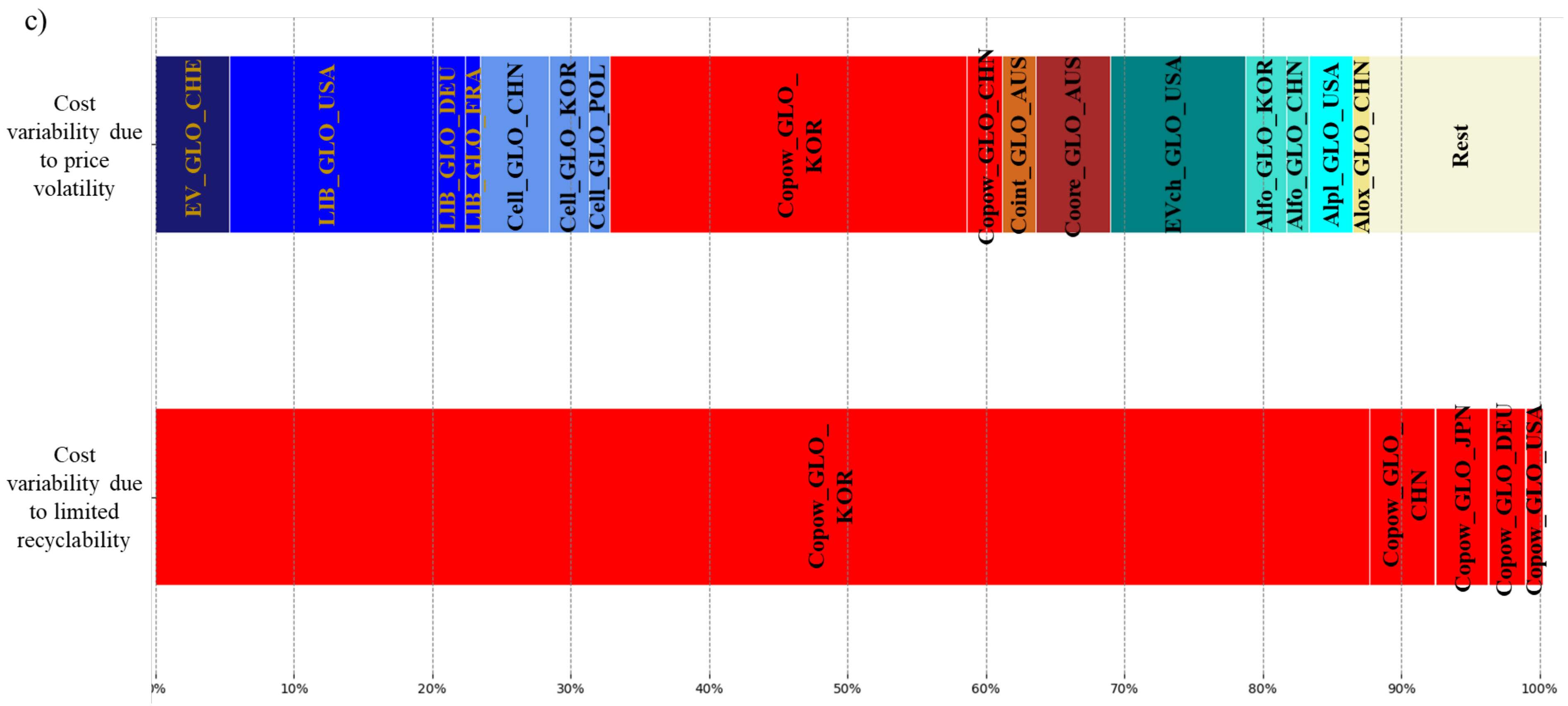

Figure B3 (continued)

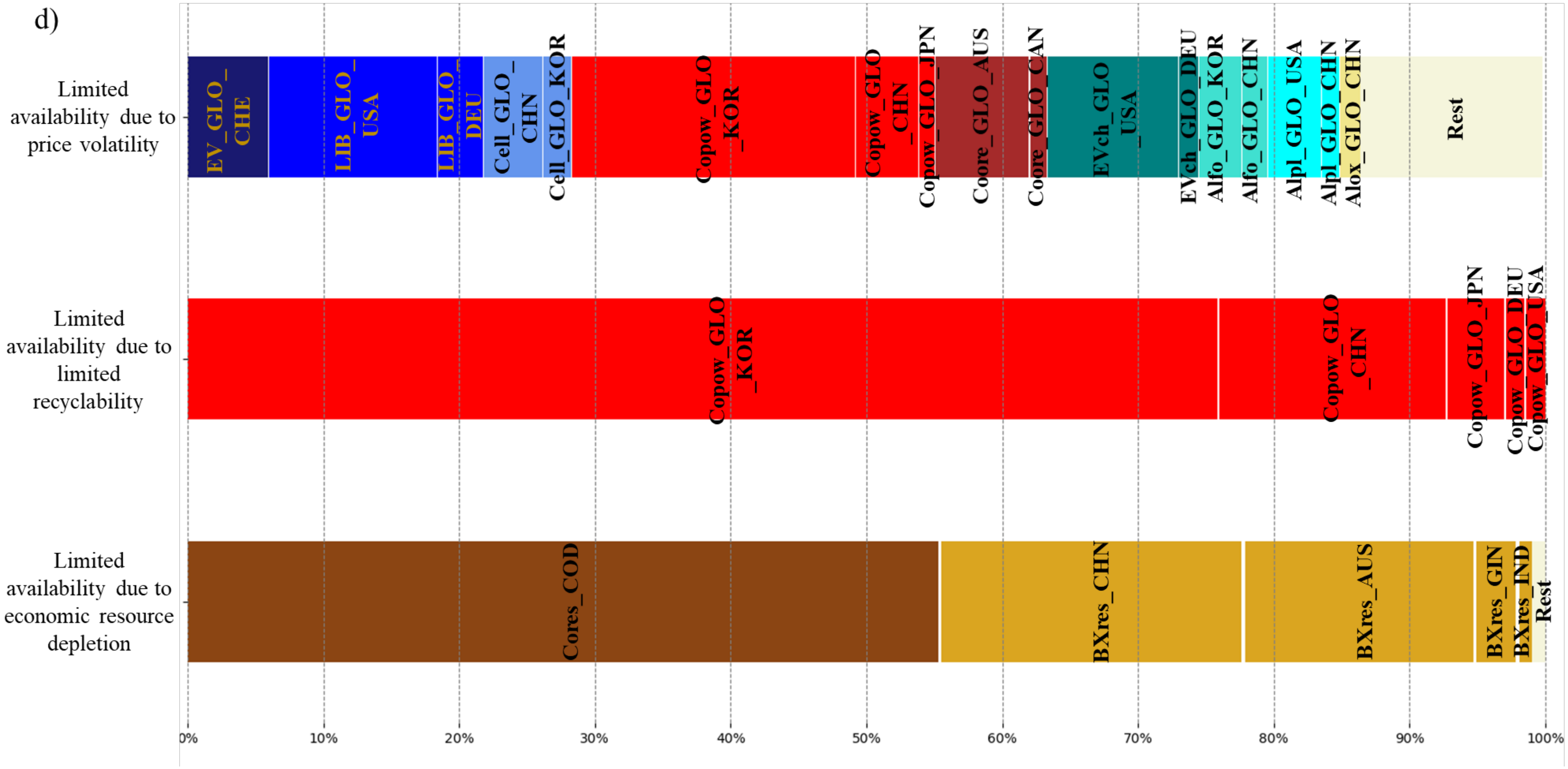

Figure B3 (continued)

Appendix C

Parts of Appendix C corresponds to the Supporting Information of Berr et al. (forthcoming), which is currently under review at the Journal of Cleaner Production.

C.1. Considered Harmonized System codes

Table C1 represents the materials/products and a description of the related 6-digit Harmonized System (HS) codes considered in the case study.

Table C1: List of materials/products and related Harmonized System (HS) codes considered in the case study. The descriptions of the 6-digit HS codes are based on the information provided by the World Customs Organization (2021).

Material/Product	HS codes	Description
Mobility sector - final products		
Battery electric cars	870380	Vehicles; with only electric motor for propulsion
Plug-in hybrid electric cars	870370 / 870360	Vehicles; with both compression-ignition or spark-ignition internal combustion piston engine and electric motor for propulsion, capable of being charged by plugging to external source of electric power
Hybrid electric cars	870350 / 870340	Vehicles; with both compression-ignition or spark-ignition internal combustion piston engine and electric motor for propulsion, incapable of being charged by plugging to external source of electric power
Battery electric busses	870240	Vehicles; public transport type with only electric motor for propulsion
Internal combustion engine cars	870321 / 870322 / 870323 / 870324 /	Vehicles; with only spark-ignition internal combustion piston engine
	870331 / 870332 / 870333	Vehicles; with only compression-ignition internal combustion piston engine
Internal combustion engine buses	870210	Vehicles; public transport type, with only compression-ignition internal combustion piston engine

Table C1 (continued)

Material/Product	HS codes	Description
Internal combustion engine trucks	870421 / 870422 / 870423 / 870431 / 870432	Vehicles; with only compression-ignition or spark –ignition internal combustion piston engine, for transport of goods
Energy sector – final products		
Solar panels	854140	Electrical apparatus; photosensitive, including photovoltaic cells, whether or not assembled in modules or made up into panels
Wind turbines (including engine, generator system and rotor)	841280	Engines; pneumatic power engines and motors
	850231	Electric generating sets; wind-powdered
Nuclear power (including fuel elements and reactor control rods)	840130	Fuel elements (cartridges); non-irradiated
	840140	Nuclear reactors; parts thereof
Hydropower turbines	841011 / 841012 / 841013	Turbines; hydraulic turbines and water wheels
Generators	850161	Generators; AC generators
	850162 / 850163 / 850164	Electric generator; AC generators
	850180	Electric generator; photovoltaic AC generators
Storage Batteries	850720	Electric accumulators; lead-acid
	850760	Electric accumulators; lithium-ion
ICT sector – final products		
Smartphones and other mobile phones	851712	Telephones for cellular networks or for other wireless networks
Laptops and Tablets	847130	Automatic data processing machines; portable, weighting not more than 10kg, consisting of at least a central processing unit, a keyboard and a display
Desktop computer	847141 / 847149	Automatic data processing machines

Table C1 (continued)

Material/Product	HS codes	Description
Flat screen monitors	852852 / 852859	Monitors other than cathode-ray tube
Flat screen TVs	852872 / 852873	Reception apparatus for television
Cathode-ray tube TVs and monitors	852842 / 852849	Cathode-ray tube monitors
	854011 / 854012	Tubes; cathode-ray television picture tubes
Mobility sector – intermediate products		
Lead-acid batteries	850710	Electric accumulators; lead-acid, of a kind used for starting piston engines
Car, bus and truck bodies (including car bodies and glass of windows, mirrors and lamps)	870710	Vehicles; bodies for electric vehicles
	870790	Vehicles; bodies for internal combustion engine vehicles
	700910	Glass; rear-view mirrors for vehicles
	853932	Lamps
	851220	Lighting or visual signaling equipment used on motor vehicles
Car or bus andtruck chassis (including the structure, axles, gear boxes, brakes, suspension, steering system, wheels and tires)	870600 /	Chassis; fitted with engines, for the motor vehicles
	870850 /	Vehicle parts; drive-axles and non-driving axles; parts thereof
	870840 /	Vehicle parts; gear boxes and parts thereof
	870880	Vehicle parts; suspension systems and parts thereof
	870870	Vehicle parts; road wheels and parts and accessories thereof
	401120 / 401110	Rubber; new pneumatic tyres used on buses or lorries and motor cars
	841221	Engines; hydraulic power engines and motors
Vehicle wiring	854430	Insulated electric conductors, wiring sets
Instrumental panel and Heating, ventilation and air conditioning	910400	Clocks; instrument panel clocks and clocks of similar type for vehicles, aircraft, spacecraft or vessels
	870891	Vehicle parts; radiators and parts thereof
	841520	Air conditioning machines

Table C1 (continued)

Material/Product	HS codes	Description
Electric motor	850132 / 850133	Electric motors and generators; DC
	850152 / 850153	Electric motors; AC motors, multiphase
Internal combustion engine	840820	Engines; compression-ignition internal combustion piston engines
	840731 / 840732 / 840733 / 840734	Engines; reciprocating piston engines
	842123	Machinery; filtering or purifying machinery, oil or petrol filters for internal combustion engines
	841231 / 841239	Engines; pneumatic power engines and motors
Exhaust	870892	Vehicle parts; silencers (mufflers) and exhaust pipes; parts thereof
Fluids	381900	Hydraulic fluids; for brakes and other prepared liquids for hydraulic transmission
	382000	Anti-freezing preparations and prepared de-icing fluids
	340220	Washing and cleaning preparations
	350610	Glues or adhesives
Al wire	760521 / 760529	Aluminium; alloys, wire
Safety glass used for vehicles	700711 / 700721	Glass; safety glass suitable for incorporation in vehicles, aircraft, spacecraft or vessels
Niobium alloys	720293	Ferro-alloys; ferro-niobium
Equipment of internal combustion engine	851110 / 851120 / 851130 / 851140 / 851150	Ignition or starting equipment, spark plugs, ignition magnetos, magneto-dynamos and magnetic flywheels, distributors and ignition coils, starter motors and generators, other generators
	841330	Pumps for internal combustion piston engines
Energy sector – intermediate products		
Safety glass used for solar panels	700719 / 700729	Glass; safety glass, toughened or laminated

Table C1 (continued)

Material/Product	HS codes	Description
Semiconductors used in solar cells	854150	Electrical apparatus; photosensitive semiconductor devices; including photovoltaic cells
Fiberglass used in wind turbines	701911 / 701912 / 701919	Glass fibres (including glass wool), chopped strands, rovings, threads and mats
Water turbine parts	841090	Turbines; parts of hydraulic turbines and water wheels, including regulators
ICT sector – intermediate products		
Nickel-cadmium batteries used in mobile phones	850730	Electric accumulators; nickel-cadmium
Nickel-metal hydride batteries used in mobile phones	850750	Electric accumulators; nickel-metal hydride
Parts of the mobile phones	851770	Telephone sets and other apparatus for the transmission or reception of voice, images or other data via a wired or wireless network; parts
Processors of laptops and computers	847150	Units of automatic data processing machines; processing units
Storage units of laptops and computers	847170	Units of automatic data processing machines; storage units
Equipment of laptops and computers	847330	Machinery; parts and accessories of the machines of heading no. 8471
Parts of flat screen monitors and televisions	852990	Reception and transmission apparatus; for use with the apparatus of heading no. 8524. To 8528
Parts of CRT monitors and TVs	852990	Reception and transmission apparatus; for use with the apparatus of heading no. 8524. to 8528
	854091	Tubes; parts of cathode-ray tubes
SD or SIM cards	852351 / 852352	Semiconductor media; solid-state non-volatile storage devices, smart cards

Table C1 (continued)

Material/Product	HS codes	Description
Nickel-metal-hydride battery cells and cases	850790	Electric accumulators; parts
Nickel-cadmium battery cells and cases	850790	Electric accumulators; parts
Mobility / Energy / ICT sectors – intermediate products		
Permanent magnets	850511	Magnets; permanent magnets
Al plate	760612 / 760692	Aluminium; plates, sheets and strip
Al foil	760719	Aluminium; foil
Mobility / Energy sectors – intermediate products		
Vanadium alloys	720292	Ferro-alloys; ferro-vanadium
Lithium-ion batteries	850760	Electric accumulators; lithium-ion
Electronics	854231 / 854232 / 854233	Electronic integrated circuits; processors, controllers, memories and amplifiers
	853221 / 853222 / 853223 / 853224	Electrical capacitors
	853400 / 853710	Printed circuit boards
	853610	Circuit breakers
Lithium-ion battery cells and cases	850790	Electric accumulators; parts
Lead-acid battery cells and cases	850790	Electric accumulators; parts

Table C1 (continued)

Material/Product	HS codes	Description
Raw materials		
Antimony powder	811010	Antimony and articles thereof; unwrought antimony, powders
Aluminium unwrought	760110 / 760120	Aluminium; unwrought, (not alloyed) / unwrought, alloys
Barytes	251110	Barium sulphate (barytes); natural
Beryllium powders	811212	Beryllium and articles thereof; unwrought beryllium, powders
Borates	284011 / 284019	Borates; disodium tetraborate (refined borax)
Cobalt powder	810520	Cobalt; mattes and other intermediate products of cobalt metallurgy, unwrought cobalt, powders
Fluorocarbons	290331 / 290339	Fluorinated, brominated or iodinated derivates of acyclic hydrocarbons
Gallium powder	811292	Gallium, germanium, hafnium, indium, niobium (columbium), rhenium and vanadium unwrought, including waste and scrap, powders
Hafnium powder	811292	Gallium, germanium, hafnium, indium, niobium (columbium), rhenium and vanadium unwrought, including waste and scrap, powders
Indium powder	811292	Gallium, germanium, hafnium, indium, niobium (columbium), rhenium and vanadium unwrought, including waste and scrap, powders
Rare Earth Elements	280530	Earth-metals, rare; scandium and yttrium, whether or not intermixed or interalloyed
Lithium	283691 /	Carbonates; lithium carbonate
	282520	Lithium oxide and hydroxide
Magnesium powders	810430	Magnesium; raspings, turnings and granules, graded according to size, powders
Natural graphite	250410 / 250490	Graphite; natural
Natural rubber	400110 / 400122 / 400129	Rubber; natural rubber latex, technically specified natural rubber, natural

Table C1 (continued)

Material/Product	HS codes	Description
Niobium powder	811292	Gallium, germanium, hafnium, indium, niobium (columbium), rhenium and vanadium unwrought, including waste and scrap, powders
Platinum group metal	711011	Metals; platinum, unwrought or in powder form
	711041	Metals; iridium, osmium, ruthenium, unwrought or in powder form
Phosphoric acid	280920	Phosphoric acid and polyphosphoric acids
Scandium	280530	Earth-metals, rare; scandium and yttrium
	284690	Compounds, inorganic or organic (excluding cerium), of rare-earth metals, of yttrium, scandium or of mixtures of these metals
Silicon metal	280461 / 280469	Silicon; containing by weight not less than or less than 99.99% of silicon
Tantalum powder	810320	Tantalum; unwrought, powders
Titanium powder	810820	Titanium; unwrought, powders
Vanadium powder	811292	Gallium, germanium, hafnium, indium, niobium (columbium), rhenium and vanadium unwrought, including waste and scrap, powders
Tungsten powder	810110 / 810194	Tungsten (wolfram); articles thereof, including waste and scrap, powders or unwrought, including bars and rods obtained simply by sintering
Strontium powder	281640	Oxides, hydroxides and peroxides, of strontium or barium
Intermediate raw materials		
Antimony oxides	282580	Antimony oxides
Aluminium oxide	281820	Aluminium oxide; other than artificial corundum
Aluminum waste & scrap	760200	Aluminium; waste and scrap
Beryllium waste & scrap	811213	Beryllium; waste and scrap
Boric acid	281000	Oxides of boron; boric acids

Table C1 (continued)

Material/Product	HS codes	Description
Co intermediates (Co mattes, Nickel-cobalt mattes, Nickel-cobalt sulfides)	810520	Cobalt; mattes and other intermediate products of cobalt metallurgy, unwrought cobalt, powders
	750110	Nickel; nickel mattes
	750120	Nickel; oxide sinters and other intermediate products of nickel metallurgy
Cobalt waste and scrap	810530	Cobalt; waste and scrap
Hydrogen fluoride	281111	Hydrogen fluoride (hydrofluoric acid)
Magnesium unwrought	810411 / 810419	Magnesium; unwrought, containing at least or less than 99.8% by weight of magnesium
Magnesium waste & scrap	810420	Magnesium; waste and scrap
Tantalum waste & scrap	810330	Tantalum; waste and scrap
Titanium oxides	282300	Titanium oxides
Titanium waste & scrap	810830	Titanium; waste and scrap
Vanadium oxides	282530	Vanadium oxides and hydroxides
Ferro-Tungsten	720280	Ferro-alloys; ferro-tungsten and ferro-silico-tungsten
Tungsten waste & scrap	810197	Tungsten (wolfram): waste and scrap

C.2. Definition of indicator thresholds

Table C2 represents the values considered for the definition of the thresholds that are used in the screening procedure described in Figure 22.

Table C2: Identification of thresholds used for step 5 of the screening procedure described in Figure 22. Thresholds marked in yellow color are defined based on the inventory flow amounts (m) multiplied by the values of the indicator for vulnerability to physical shortage (PVI) and the values of the indicator for economic importance/damage (EVI) that describe hotspots in the case study *Short-term assessment of electric vehicles used in Switzerland* performed in section 4. The abbreviations of the countries are based on the alpha-3 codes and the abbreviations of materials/products are defined as follows: Electric vehicle (EV), Lithium-ion battery (LIB), Lithium-ion battery cell (Cell), Electric vehicle wiring (EV_wi), Aluminium wire (Al_wi), Cobalt ore (Co_ore), Bauxite ore (BX_ore)

Inventory flows associated to supply disruption hotspots	**Values for *m*PVI***	**Values for *EVI***	
		Cost variability	**Limited availability**
EV flow from USA to CHE	3.89E-04	0.41	1.00
EV flow from DEU to CHE	1.38E-04	0.20	1.00
EV flow from FRA to CHE	7.56E-05	No hotspot value	1.00
LIB flow from CHN to USA	8.97E-05	0.13	0.26
LIB flow from CHN to DEU	2.95E-05	No hotspot value	0.20
LIB flow from KOR to DEU	3.38E-05	No hotspot value	0.20
Cell flow from KOR to POL	8.44E-05	0.13	0.08
EV_wi flow from MEX to USA	2.80E-04	0.24	0.26
EV_wi flow from CHN to KOR	5.53E-05	**0.04**	No hotspot value
Al_wi flow from BHR to MAR	1.20E-04	0.05	0.08
Co_ore flow from COD to AUS	7.97E-04	0.33	0.49
Co_ore flow from COD to CAN	3.06E-04	0.13	0.23
Co_ore flow from COD to CHN	2.02E-04	0.08	0.05
Co_ore flow from COD to PHL	9.78E-05	**0.04**	No hotspot value
Co_ore flow from COD to USA	1.06E-04	**0.04**	No hotspot value
BX_ore flow from GIN to CHN	**1.99E-05**	No hotspot value	0.17
BX_ore flow from AUS to CHN	3.12E-05	No hotspot value	0.17

C.3. Explanation of supply chain quantification

As shown in Figure 24, different procedures and types of data are considered to quantify the flows of fuels and the flows of final products, materials/intermediate products and minerals. Following, the quantification of the different types of flows is explained.

Quantification of final product and fuel flows:

At first, the reference amount is defined in accordance with the functional unit. Considering the differences in the functional units used for the hotspot analysis and for the comparison of overall impacts (see section 5.1.1), different reference amounts are considered in these two cases. Regarding the hotspot analysis, the total Swiss consumption of the considered final products and fuels describes the reference amount. Regarding the impact comparisons, the amounts of final products and fuels providing the same service represent the reference amount. After defining the reference amounts, the domestic production amounts and import amounts of final products and fuels used in Switzerland are determined. Table C3 shows these amounts exemplarily for the performed hotspot analysis.

The data sources used to define the domestic production and import amounts of final products are listed in Table C3a. While these import amounts are specified with import data from BACI, these domestic production amounts are ideally determined based on literature related to Swiss production. An example is the study of Moresi (2018), which informs about the production amount of vehicles in Switzerland. If such sources are not available, country-specific production statistics such as the one published by Yu and Sumangil (2021) reporting the production amounts of lithium-ion batteries per country are consulted. If such statistics are also not found, the export shares defined based on trade data from BACI (Gaulier and Zignago 2010) are considered as an approximation of country-specific production amounts.

The data sources used to define the domestic production and import amounts of fuels are listed in Table C3b. The total Swiss import amounts of the individual fuels are determined based on the *Schweizerische Gesamtenergiestatistik 2020* published by the BFE (2020a). The country-specific import share and domestic production amounts are defined by considering the production statistics per country for the different fuels.

Table C3: Description of Swiss import and domestic production amounts for a) final products and b) fuels. Import amounts for final products are determined based on trade data from BACI (Gaulier and Zignago 2010) and import amounts for fuels are defined as described in the tab "Fuel_flows" of the Excel sheet provided in the Files 9 of the data repository D.2.

a) Final products

Commodity	Import amount (in tons)	Domestic production (in tons)	Data sources
Battery electric car	39'558	0	Imports: BACI Domestic production: (Moresi 2018), (OICA 2023)
Plug-in hybrid electric car	33'180	0	
Hybrid electric car	55'704	0	
Internal combustion engine car	318'186	0	
Battery electric bus	452	0	
Hybrid electric bus	287	0	
Internal combustion engine bus	8'031	0	
Internal combustion engine truck	78'751	0	
Solar panels	29'169	0	Imports: BACI Domestic production: (Campbell 2022)
Wind turbines	1'315	0	Imports: BACI Domestic production: (Jaganmohan 2022), (Ingram 2020)
Alternating current generators	1'034	0	Imports & domestic production: BACI
Nuclear power plant equipment	111	0	
Hydropower plant equipment	262	0	
Storage lithium-ion battery	167	0	Imports: BACI Domestic production: (Yu and Sumangil 2021), (Mayyas et al. 2019)
Storage lead-acid battery	4'025	0	Imports & domestic production: BACI
Mobile phones and tablets	1'146	0	
Laptops	4'613	0	
Desktop computers	1'726	0	

Table C3 (continued)

Commodity	Import amount (in tons)	Domestic production (in tons)	Data sources
Flat screen monitors	9'437	0	Imports & domestic production: BACI
Flat screen televisions	8'979	0	
Cathode-ray tube monitors/televisions	23	0	

b) Fuels

Commodity		Import amount (in GWh)	Domestic production (in GWh)	Data source
Petroleum oil		82.80	0	Total import: (BFE 2020a) Country-specific import shares: (FDFA 2023) Domestic production: (eia 2022)
Electricity*	Natural gas	5.13	29.20	Imports: (BFE 2020a), (Malerba et al. 2022) Country-specific import shares: (Krecke 2022), (Pandey 2022), (Nakhle 2022) Domestic production: (the GlobalEconomy.com 2020), (eia 2022), (Garside 2023), (Loesche 2017)
	Coal	3.34		
	Uranium	13.71		
Natural gas		24.04	0	Imports: (BFE 2020a) Country-specific import shares: (Krecke 2022) Domestic production: (worldometer 2017)
Coal		1.02	0	Imports: (BFE 2020a) Country-specific import shares: (Pandey 2022) Domestic production: (Garside 2023)
Fuel wood		8.01	0	Imports: (BFE 2020a) Country-specific import shares: (TrendEconomy 2021) Domestic production: (Federal Office for the Environment 2021)

*The electricity mix of the European Union (Malerba et al. 2022) is considered for defining the country-speicfic import amounts of fuels.

Quantification of mineral and material/intermediate product flows:

The trade data related to the considered materials/intermediate products (see list of these materials/products in Table C1) are acquired from the BACI database (Gaulier and Zignago 2010). The country-specific trade amounts are then defined by considering the adjustments related to the content of the HS codes explained in File 5 of the data repository D.2.

In the extraction stage of the supply chain, the trade amounts of the considered minerals are not determined based the HS codes provided by the World Customs Organization (2021), but extraction rates from the British Geological Survey (Idoine et al. 2022) or the United States Geological Survey (USGS 2020) are used as an approximation for the definition of trade amounts. Data from these geological surveys instead of data from the BACI trade database are used because, as explained by BGR (2021) for the case of cobalt mining, the trade flows of ores and concentrates may only insufficiently be reported due to traceability issues of artisanal supply chains.

After trade amounts have been defined, the global average weight ratios are multiplied by these amounts in order to identify the amounts of materials or intermediate products required for the production of the material/product output. These weight ratios are collected from the literature including for example scientific articles, reports or websites. The weight ratios and the related data sources used to quantify the supply chain are provided for raw materials and intermediate products in the tab "Weight%" of the Excel sheets provided in the Files 1 to 3 of the data repository D.2. At the raw material production stages (i.e. the mining, processing and refining stages that correspond to supply chain tiers 4 to 6 in Figure 21), the global average weight ratios are defined by metal contents. The metal contents of the (intermediate) raw materials and minerals are described in Table C4. For some of the raw materials, the metal contents are estimated as 100% based on information from the United States Geological Survey (USGS 2020) and the World Customs Organization (2021). These raw materials are antimony powder, aluminium unwrought, barytes, beryllium powder, cobalt powder, fluorocarbons, gallium powder, hafnium powder, indium powder, rare earth elements, magnesium powder, natural graphite, natural rubber, PGMs, phosphoric acid, scandium, silicon metal, tantalum powder, titanium powder, vanadium powder and tungsten powder.

Table C4: Pure metal contents of (intermediate) raw materials and minerals

Material	Metal content in wt%	Data source
Raw material		
Borates	11.34%	(Harper et al. 2012)
Lithium carbonates and oxides	19.00%	(Azevedo et al. 2018)
Niobium powder (ferroniobium)	65.00%	(metalshub 2021)
Strontium oxide	84.56%	(TranslatorsCafe.com 2017)
Intermediate raw material		
Antimony oxide	99.60%	(Alfa Aesar 2023)
Aluminium oxide	52.00%	(Liu and Muller 2013)
Aluminium waste & scrap	90.00%	(Gopienko 2019)
Beryllium waste & scrap	2.00%	(Cunningham 2004)
Boric acid	17.48%	(Harper et al. 2012)
Cobalt intermediates	27.00%	(Baars et al. 2021)
Cobalt waste & scrap	4.00%	(Godoy León et al. 2022)
Hydrogen fluoride	97.00%	(Wikipedia 2022)
Magnesium unwrought	99.80%	(OEC 2020)
Magnesium waste & scrap	90.00%	(Lucci et al. 2015)
Tantalum waste & scrap	70.00%	(Mancheri et al. 2018)
Titanium oxide	59.95%	(Brittain et al. 1992)
Titanium waste & scrap	85.59%	(Rotmann et al. 2011)
Vanadium oxide	56.00%	(World Health Organization 2000)
Ferro-tungsten	75.00%	(Westbrook Resources Ltd 2023)
Tungsten waste & scrap	67.50%	(Shemi et al. 2018)

Table C4 (continued)

Material	Metal content in wt%	Data source
Minerals		
Antimony ore	72.00%	(Minerals Education Coalition 2023)
Bauxite ore	48.00%	(Liu and Muller 2013)
Baryte ore	58.00%	(British Geological Survey 2006)
Beryllium ore	4.00%	(USGS 2021b)
Borate mineral	11.34%	(Harper et al. 2012)
Cobalt ore	10.00%	(Godoy León et al. 2021), (Sun et al. 2019), (Baars et al. 2021)
Fluorspar	48.90%	(British Geological Survey 2010)
Gallium ore	0.005%	(Foley and Jaskula 2013)
Hafnium ore	0.0045	(Ireland 2014), (Mendoza et al. 2010)
Indium ore	0.135%	(Paradis 2015)
Rare Earth Oxides	5.00%	(Zhou et al. 2017)
Lithium ore	1.50%	(SGS Minerlas Services 2010)
Magnesium ore	28.83%	(Barthelmy 2014)
Niobium ore	2.50%	(Alves and Coutinho 2019)
Platinum Group Metals ore	0.0003%	(Sluzhenikin 2011)
Phosphate rock	30.00%	(Liang et al. 2017)
Scandium ore	0.001%	(Wang et al. 2020)
Silicon ore	46.75%	(Stewart and Simmons 2018)
Tantalum ore	30.30%	(USGS 2022g)
Titanium ore	52.50%	(El Khalloufi et al. 2021)
Vanadium ore	12.00%	(Silin et al. 2020)
Tungsten ore	64.00%	(Damdinova and Damdinov 2021)
Strontium ore	43.88%	(USGS 2022a)

When the required production amounts of materials/intermediate products have been defined, the domestic production amounts are estimated in order to determine the share of these materials/intermediate products that need to be acquired from imports. The data used for calculating the domestic production amounts comprises country-specific import amounts and country-specific production amounts. Country-specific import amounts are defined based on data from BACI. The country-specific production amounts are estimated based on global production amounts and country-specific production shares. The global production amounts of final products are collected from production statistics in the literature such as the one for vehicles published by OICA (2023). The global production amounts of materials/intermediate products are defined by multiplying the production amounts of the process output with the related weight ratios. Country-specific production shares are defined based on material/product-specific production statistics per country such as the one for traction batteries published by Yu and Sumangil (2021). However, as such statistics are not always available, export data from BACI are used as an approximation to define the country-specific production shares. The values and data sources related to the definition of domestic production amounts are represented in the Excel sheets provided in the Files 6 to 8 of the data repository D.2.

C.4. Indicator quantification and related data sources

Table C5 provides an overview of the equations and data sources that are applied for the quantification of the indicators used to define the considered characterization factors.

Table C5: Overview of the quantification of indicators used for the definition of the considered characterization factors

Indicator	Equation	Data source
Indicator for supply disruption event over a period (EI*t)		
Indicator for geopolitical instability (GI)	$GI = \frac{100 - WGI(PS)}{100}$ WGI(PS): Worldwide Governance Indicator (Political Stability and Absence of Violence/Terrorism)	(World Bank 2019)
Indicator for trade barriers (TB)	$TB = \frac{100 - TABI}{100}$ TABI: Trading Across Borders Indicator	(World Bank 2020)

Table C5 (continued)

Indicator	Equation	Data source
Indicator for child labor restrictions (CLR)	$CLR = (CLI * 0.2)$ CLI: Indicator of child labor risk	Social Hotspot Database (Benoit Norris et al. 2019)
Indicator for price volatility (PV)	$market\ price = \frac{global\ cost}{global\ mass}$ $PV = \frac{highest\ market\ price\ (last\ 3\ years)}{lowest\ market\ price\ (last\ 3\ years)}$ Barium ore prices: (USGS 2022e) Beryllium ore prices: (Trueman and Sabey 2014) Borates prices: (Mermer and Şengül 2020) Boric acid prices: (statista 2023) Boron prices: (USGS 2022h) Lithium ore prices: (Sun 2022), (USGS 2022b) Magnesium powder prices: (USGS 2022c) Rare Earth prices: (USGS 2022d) Fuel prices: (TradingEconomics 2023) (see price conversions in tab "Prices" in Excel sheet provided in File 9 of the data repository D.2)	BACI (Gaulier and Zignago 2010)
Indicator for limited recyclability (LR)	$LR = 100\% - EoLRR$ EoLRR: End-of-life recycling rate EoLRR for natural graphite: (Sabarny et al. 2021); EoLRR for natural rubber: (Akbas and Yuhana 2021); The E-waste EoLRR reported by Forti et al. (2020) is considered for phosphoric acid.	(Coughlan and Fitzpatrick 2020)
Indicator for economic resource depletion (ERD)	$ERD = \frac{extraction\ rate - replenishment\ rate}{economic\ resource\ stock}$ The replenishment rate is assumed as 0 for all considered materials. Extraction rates of hafnium, scandium and silicon are acquired from USGS (2022i, 2022j, 2022f)	Extraction rate: (Idoine et al. 2022) Economic resource stock: (USGS 2020)
Indicator for event duration (t)	t	Estimated based on author judgment
Indicator for supply diversity (DI)		
Indicator for resource concentration	$DI = 100\%$	

Table C5 (continued)

Indicator	Equation	Data source
Indicator for market concentration (used in combination with indicators for country-specific events)	$$DI = \frac{import}{country\ production + import}$$	Import amounts: BACI (Gaulier and Zignago 2010) Country-specific production amounts: see the Excel sheets provided in the Files 6 to 9 of the data repository D.2.
Indicator for production concentration (used in combination with indicators for global events)	$$HHI = \left(\frac{country\ production}{global\ production}\right)^2 + \sum_n \left(\frac{country\ production_n}{global\ production}\right)^2$$ n: production countries	Country-specific production amounts: see the Excel sheets provided in the Files 6 to 8 of the data repository D.2.
Indicator for vulnerability to physical shortage (PVI)		
Indicator for vulnerability to physical shortage (PVI)	$$PVI = \frac{global\ production}{(global\ in\ use\ stock)^2}$$	Country-specific production amounts and in-use stock: see data in the Excel sheets provided in the Files 6 to 9 of the data repository D.2.
Indicator for economic importance or economic damage (EVI)		
Indicator for economic importance (used for analysis of cost variability (CV))	$$EVI(CV) = \frac{m * \frac{cost_{country\ specific}}{mass_{country\ specific}}}{cost_{supply\ chain}}$$ m: inventory flow amount $cost_{supply\ chain}$: total cost of the material accumulated for the supply chain	Inventory flow amount: defined based on the procedure described in section 4.1.3. Cost and mass: BACI (Gaulier and Zignago 2010) Country-specific production amounts: see the Excel sheets provided in the Files 6 to 8 of the data repository D.2.
Indicator for economic damage (used for analysis of limited availability (LA))	$EVI(LA) =$ $$\frac{\sum_i \left(m_{output,i} * \frac{cost_{output,i}}{mass_{output,i}}\right) * \left(1 - \frac{country\ production_{input}}{country\ market_{input}}\right)}{cost_{supply\ chain}}$$ Input: the used material for a process in country i Output: the produced product of a process in country i $$country\ market = country\ production + import$$	

C.5. Flowcharts of the Swiss mobility, energy and ICT sectors

Figures C1, C2 and C3 represent the material/product flows that are illustrated in Figure 25 on the level of each sector.

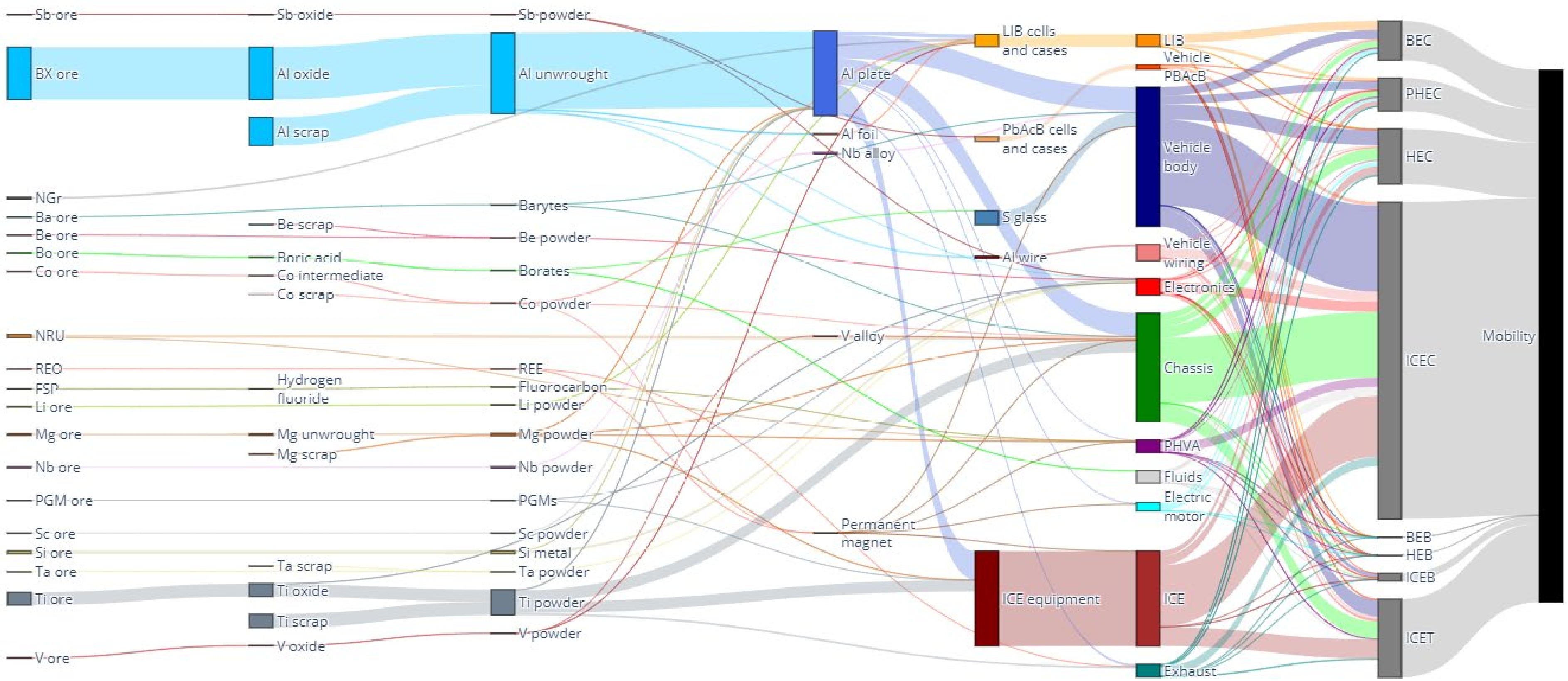

Figure C1: Flowchart of materials/products used within the Swiss mobility sector.
Abbreviations for materials/products are provided in Figure 25.

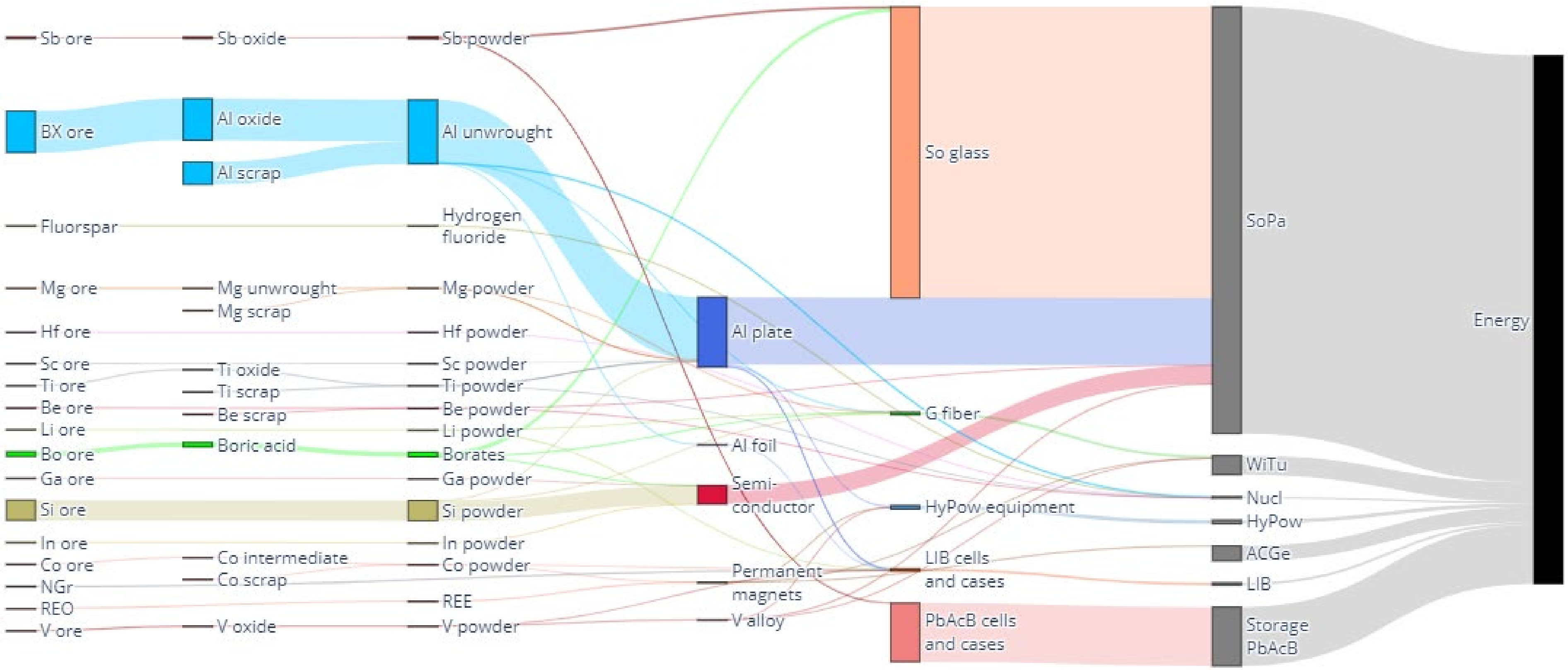

Figure C2: Flowchart of materials/products used within the Swiss energy sector. Abbreviations for materials/products are provided in Figure 25.

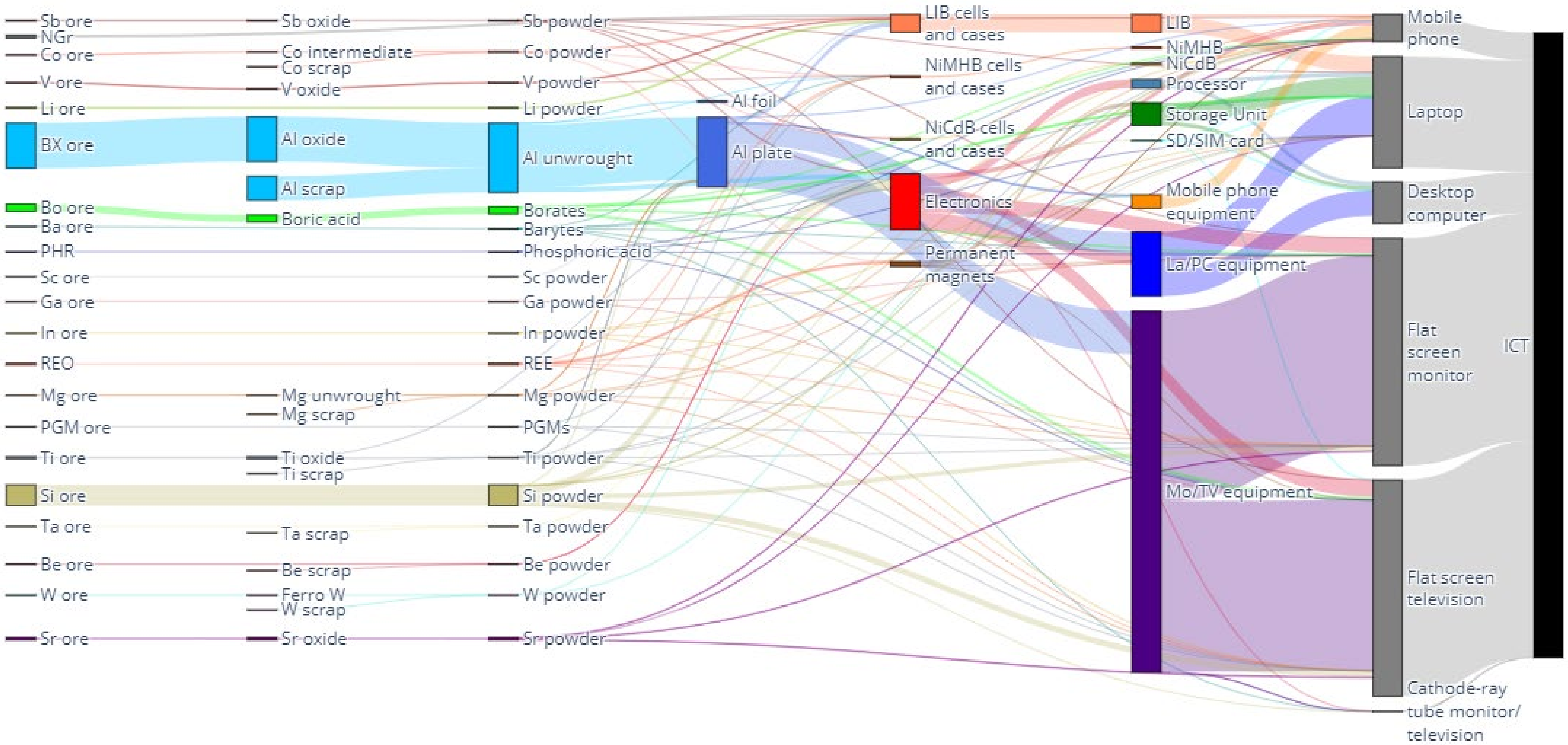

Figure C3: Flowchart of materials/products used within the Swiss ICT sector.
Abbreviations for materials/products are provided in Figure 25.

C.6. Hotspot contribution analysis

Figure C4 presents the results of the hotspot contribution analysis for the individual material/product and fuel flows on the level of the impact category.

Figure C4: Magnitude of hotspots within supply chains of the Swiss economy
considering cost variability and limited availability related to flows of materials/products and fuels. Abbreviations for the materials/products are explained in Figure 27 and abbreviations for countries are based on alpha-3 codes (GLO refers to flows originating from the global market).

Appendix D

Appendix D includes the links to the data repository on Github.

D.1. Github data repository for Chapter 4

Data for: *Assessing Short-Term Supply Disruption Impacts within Life Cycle Sustainability Assessment – a Case Study of Electric Vehicles*

https://github.com/marcusberr/Supplementary-data-for-Dissertation-Marcus-Berr/tree/main/Chapter%204

Content of repository:

File 1: Adjustments related to the content of considered HS Codes (Chapter 4).docx

File 2: Inventory flows_Swiss_EV.xlsx

File 3: LCIA data LIB & EV.xlsx

File 4: LCIA data EV body, motor, chassis & wiring.xlsx

File 5: LCIA data Al foil, plate & wire.xlsx

File 6: LCIA data Co mining & processing.xlsx

File 7: LCIA data Al ore, oxide & unwrought.xlsx

File 8: Geopolitical instability indicator.xlsx

File 9: Trading Across Borders Indicator score.xlsx

File 10: Price volatility indicator.xlsx

File 11: Depletion potential indicator.xlsx

D.2. Github data repository for Chapter 5

Data for: *Assessment of Short-Term Supply Disruption Impacts for the Swiss Mobility, Energy and ICT Sectors – Application of the SPOTTER Approach*

https://github.com/marcusberr/Supplementary-data-for-Dissertation-Marcus-Berr/tree/main/Chapter%205

Content of repository:

File 1: Data_Sankey_Mobility.xlsx

File 2: Data_Sankey_Energy.xlsx

File 3: Data_Sankey_ICT.xlsx

File 4: Data_Sankey_Economy.xlsx

File 5: Adjustments related to the content of considered HS Codes (Chapter 5).docx

File 6: LCIA_Mobility.xlsx

File 7: LCIA_Energy.xlsx

File 8: LCIA_ICT.xlsx

File 9: LCIA_fuel.xlsx