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Research article

Social LCA for rare earth NdFeB permanent magnets

Jasmin Werker, Christina Wulf*, Petra Zapp, Andrea Schreiber, Josefine Marx

Forschungszentrum Jülich, Institute of Energy and Climate Research - Systems Analysis and Technology Evaluation (IEK-STE), D-52425 Jülich, Germany

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ABSTRACT

Rare earth permanent magnets are important components for modern (energy) technologies and are employed to reduce GHG emissions and combat climate change. The process of extracting these minerals from the ore has contentious economic, environmental and social implications. While the environmental impacts of their production have already been analyzed in several studies, the economic and the social perspective is still under-researched. The Social Life Cycle Assessment (S-LCA) approach employed in the present research explores whether there is a difference in social risks for rare earth permanent magnet production from three different rare earth ore production locations and the associated value chains. While one is located completely in China, another is composed of processes in Australia and Malaysia. The third process chain combines processes in the United States and Japan. The Product Social Impact Life Cycle Assessment (PSILCA) 2.0 database is used to assess the social implications. The analysis focuses on value chain actors, a stakeholder group of great interest to businesses but often underrepresented in S-LCA research. The impact categories describing this stakeholder group pertain to issues of social responsibility along the value chain, fair competition and corruption. Overall, the US value chain indicates the lowest level of social risk along the supply chain. However, in order to gain a deeper understanding of the social risks a sectoral and geographical analysis is conducted. Across all three cases, the mineral, fossil fuel and chemical sectors are shown to be problematic.

1. Introduction

Climate change is probably one of the greatest challenges facing humankind. One way to combat climate change by reducing greenhouse gas emissions is to increase the share of renewable energy technologies. Several of these technologies, such as wind turbines or batteries, require rare earth elements (REEs). Global production of REEs is found predominantly in China (80% in 2017), even though only 36% of proven reserves are located there (U.S. Geological Survey, 2018).

While the environmental life cycle consequences of rare earth mining have been analyzed in a number of studies, e.g. (Zaimes et al., 2015; Sprecher et al., 2014; Vahidi and Zhao, 2017; Marx et al., 2018; Schulze et al., 2017; Lee and Wen, 2016), the social consequences have not yet been investigated as extensively. Attention is frequently focused on specific social aspects. Ali (2014) investigated social health risks caused by thorium emissions during mining as well as public engagement. A study by Li et al. (2013) focused on the accumulation of radiation in food and blood. In addition to health issues, McLellan et al. (2014) discussed the lack of trained and experienced personnel outside of China. Other groups, such as the European Commission (European Commission, 2017) or individual states have assessed the criticality of REEs by looking at the political and economic situation in producing countries.

Another frequently discussed social aspect is illegal mining in China. Approx. 40% of ion adsorption clays (IACs) are mined illegally involving horrendous pollution (Packey and Kingsnorth, 2016). In total the share of the illegal rare earth sector ranges between 22 and 25%, representing 59 to 65% of heavy rare earth and 14 to 16% of light rare earth mining (Nguyen and Imholte, 2016). Although the Chinese Ministry of Environmental Protection (MEP) has already made several attempts to set stricter standards, environmental conditions have hardly been affected (Wübbeke, 2013).

Most often, these social aspects are discussed qualitatively with the emphasis on mining activities. In contrast, Bailey et al. (2017) considered an entire process chain up to the use of permanent magnet motors in the EV industry. However, they discussed the social impacts qualitatively. A first attempt to include social impacts quantitatively in a real life cycle thinking approach was made by Wulf et al. (2017). The focus here, however, was on identifying methods for combining Environmental LCA, S-LCA and Life Cycle Costing (LCC) in Life Cycle Sustainability Assessment (LCSA)

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* Corresponding author.
E-mail address: c.wulf@fz-juelich.de (C. Wulf).

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using rare earth permanent magnet production as an example. An S-LCA on REE was also undertaken in the work of Schlör et al. (2018), although major attention here was given to integration into a newly developed energy-mineral-society NEXUS. Neither study provided a detailed account of social impacts. Therefore, the present study represents the first S-LCA study on rare earth products, making use of the detailed process chain description of an earlier publication on environmental impacts by Marx et al. (2018).

While REEs are used in many modern technologies, this study focuses on those employed in permanent magnets, specifically rare earth iron boron magnets (NdFeB). Due to their technical properties, they are widely used in wind turbines, hybrid and electric vehicles (HEVs and EVs), household electrical appliances, computer hard disk drives (HDDs), and many small consumer electronic devices.

In the analysis, three different rare earth ore origins and associated value chains are compared. One is completely located in China (originating from the largest RE mine in Bayan Obo), while another is composed of processes in Australia and Malaysia (designated by the name of the Australian mine Mount Weld). The third process chain combines processes in the United States and Japan (designated by the name of the US mine Mountain Pass, which went in production again in the first quarter of 2018 after going bankrupt in 2015 (U.S. Geological Survey, 2019)). These three locations represent the three major current and past mines for rare earth production in the world. Moreover, Mountain Pass serves as an example of an industrial country in the western hemisphere as a contrast to China's socialist market economy and Malaysia's emerging economy.

The goal is to assess whether there is a difference in social risks for the value chain. Social Life Cycle Assessment (S-LCA) is chosen as an appropriate method to assess the social sustainability of the three process chains. While S-LCA generally looks at five different stakeholder groups the present study furthermore undertakes a deeper investigation value chain actors as the risks associated with this group (e.g. fair competition, corruption) are of great interest in business decisions. Using the Product Social Impact Life Cycle Assessment (PSILCA) database, a detailed analysis of sectors contributing to social risks along the life cycle from mining to magnet manufacturing is provided. This generic database is used due to the lack of primary data mainly from Chines production facilities. For that reason, in this study only hot spots are identified that will need further investigation to actually improve the social footprint of permanent magnets.

2. Social LCA

The following chapter provides an overview of S-LCA theory and practice. First, the database approach is described. The second section then describes the NdFeB magnet process chain and presents the assumptions used in this study.

2.1. S-LCA theory and database

S-LCA addresses the social implications of process chains and products from a life cycle perspective. The method has developed gradually over the past few years to respond to the rising interest in sustainability assessments of products and processes. It is based on the concept of Life Cycle Thinking, which has been applied for environmental (Life Cycle Assessment LCA) and economic assessment (Life Cycle Costing LCC) for several decades. Like LCA, the S-LCA method is based on the ISO 14040 framework (DIN EN ISO 14040:2006, 2009; DIN EN ISO 14044:2006, 2006). The method consists of four phases that are iteratively related to each other (Fig. 1). The first phase, i.e. goal and scope definition, is crucial to the whole assessment as it defines the purpose, the objective, the methodological framework and the physical system boundary. This also establishes the breadth and the depth of each step. Due to the iterative nature of the whole methodology, the goal and scope may be changed during the assessment, for example because additional information or constraints may arise. Based on the methodological framework and the system boundary, the data are collected in the Social Life Cycle Inventory. On the one hand, this includes all the material flows of the product system and on the other hand, according to the chosen S-LCA framework, complementary data for the impact assessment. In the Social Life Cycle Impact Assessment, potential social impacts are calculated either as social performance or social risk based on the chosen methodological framework. In the last phase, the interpretation, the results of the impact assessment are furthermore put into context, recommendations may be given and conclusions drawn. (Neugebauer et al., 2019)

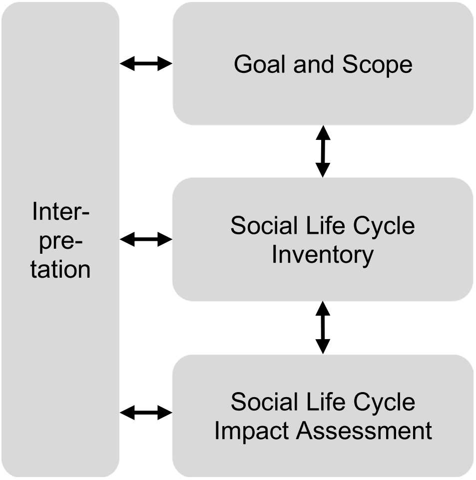

Fig. 1. Framework of S-LCA based on (DIN EN ISO 14040:2006, 2009).

In 2009, a UNEP/SETAC working group published Guidelines for S-LCA (currently under revision) that have become the lead document in S-LCA (UNEP-SETAC, 2009). S-LCA generally looks at the product/process level and social implications are more difficult to allocate to one particular product/process. Therefore, the Guidelines identify five relevant stakeholder groups for S-LCA: workers, local communities, society, value chain actors and consumers. However, data availability and precision of measurement methods differ greatly for these issues. Methods of collecting inventory data and conducting Life Cycle Impact Assessment within S-LCA also vary considerably and range from site-specific qualitative interviews, e.g. (Blom and Solmar, 2009; Siebert et al., 2016; Busset et al., 2014) to generic databases based on global economic input–output (I/O) models, e.g. (Sousa-Zomer and Cauchick Miguel, 2015; Franze and Ciroth, 2011). One of these generic databases is the PSILCA database, which identifies hotspots along a supply chain by combining an I/O model with risk-assessed indicators. Hotspots are "production activities in the product life cycle that provide a higher opportunity to address issues of concern as well as highlight potential risks" (Benoît-Norris et al., 2012). Generally, the goal of S-LCA is also to assess potential positive effects of the process/product. The ways of measuring such positive impact, for example employment effects of a new factory being built, are still under discussion. In the second version of PSILCA a first attempt at implementing positive effects into a database is included (depicted as negative numbers, the lower the number the better the result). One of the impact categories measures the contribution to economic development

Table 1
PSILCA impact categories excluded and the associated justification.

Impact category	Justification
Biomass consumption	Better described with the LCA impact category “Resource depletion, mineral, fossil and renewable”. In addition, LCA provides other impact categories, which do not account for the consumed biomass but rather assess its pollution.
Contribution to environmental load	Better described with the LCA impact categories “Acidification”, “Climate change”, “Ozone depletion”, “Particulate matter/Respiratory inorganics”, “Photochemical ozone formation”. These impact categories do not only account for the emissions but also assess their pollution potential with regard to different ecological and human health problems.
DALYs due to indoor and outdoor air and water pollution	Better described with the LCA impact categories “Human toxicity, carcinogenics”, “Human toxicity, non-carcinogenics”.
Industrial water depletion	Better described with the LCA impact category “Water scarcity” and the AWARE (assessing impacts of water consumption based on available water remaining) characterization model, which not only accounts for water depletion but also relates it to its regional scarcity.
Minerals consumption	Better described with the LCA impact category “Resource depletion, mineral, fossil and renewable”.
Fossil fuel consumption	Better described with the LCA impact categories “Resource depletion, mineral, fossil and renewable” and “Cumulative energy demand”.
Pollution level of the country	The two areas of protection “Human Health” and “Ecosystems” in LCA and their associated impact categories cover all the types of pollution that can occur in one country.

in terms of gross domestic production. This impact category is measured as opportunity instead of risk. The PSILCA database is based on the multi-regional I/O model Eora (Lenzen et al., 2013) and provides information on approximately 15,000 sectors in 189 countries (Eisfeldt and Ciroth, 2017). The hotspot analysis in PSILCA 2.0 identifies risk levels for 49 impact categories, which can be attributed to the five different stakeholder categories. Impact categories are meaningful categories for describing social phenomena. Since Marx et al. (2018) have already provided a detailed account of the environmental implications of the three value chains, seven of the impact categories with a more environmental focus are excluded from this analysis. A detailed list of the impact categories removed and why they were excluded is given in Table 1. The risk assessment for the impact categories in PSILCA is undertaken using performance reference points from international statistical agencies (e.g. the World Bank, UNICEF, ILO) and other governmental and private databases (Eisfeldt and Ciroth, 2017). The raw data needed for a PSILCA analysis are economic input per sector, which means that the physical data per material or energy flow (e.g. 1 kg of cement) must be translated into a monetary amount per sector (e.g. US$ 10 of the cement sector). Given that the price of a product determines how much of a particular sector is used within a process, this information influences the analysis significantly. In analyzing PSILCA results one needs to be aware of the uncertainties involved in the price assessment.

Within PSILCA, social impacts and the data from the I/O model are related by the use of the activity variable termed worker hours, a concept established by Norris (2006). Worker hours describe how much working time is needed to produce each US$ output of a particular sector. Therefore, the use of worker hours enables the practitioner to relativize the monetary input from a particular sector in social terms or, in other words, helps to adapt the social data to the functional unit. “Activity variables have a similar function as inventory flows in LCA” (Zimdars et al., 2017). The use of worker hours as an activity variable for all impact categories has been criticized as only being relevant to the stakeholder group of workers, which is why Zimdars et al. (2017), amongst others, have been working to identify other activity variables to better represent the other stakeholder groups. The Guidelines also suggest added value as a possible activity variable; however, currently the available generic databases only provide worker hours. Here, the different production processes were not weighted in terms of worker hours since it was not possible to obtain information for this assessment with respect to these processes. Therefore, the analysis is limited to the worker hours attribution available per input sector within the PSILCA database. The work carried out during the extraction of the ore is not taken into account.

Table 2
Characterization factors in PSILCA 2.0 (Eisfeldt, 2017).

Risk level	Characterization factor
Very low risk	0.01
Low risk	0.1
Medium risk	1
High risk	10
Very high risk	100
No risk/opportunity	0
Low opportunity	0.1
Medium opportunity	1
High opportunity	10
No data	0.1

In order to express impacts in an aggregated form for the entire supply chain Benoit-Norris and Norris (2015) also developed an impact assessment method that assigns characterization factors to the different impact categories per sector previously assessed on an ordinal scale (Eisfeldt and Ciroth, 2017). The final results are than expressed in relation to the medium risk level as medium risk hours per impact category. Table 2 shows the characterization factors used in the PSILCA impact assessment.

PSILCA provides social information about each of the sectors in the database with a risk level on an ordinal scale (Table 2). The characterization factors in the final risk calculation are used to weight a sectoral input according to the risk level. It is important to keep in mind that in most cases a missing value (‘no data’) is equated to ‘low risk’.

The stakeholder group of value chain actors (excluding consumers) has as yet rarely been represented in S-LCA case studies (Petti et al., 2018), even though the indicators can provide important insights into the social sustainability of a supply chain. When making business decisions, issues of fair competition and corruption are decisive. Therefore, this study investigates this stakeholder group in detail, also in order to uncover possible methodological issues and identify room for improvement. However, the impact categories for measuring risks related to this group in a quantitative and generic manner have not yet been well established. Therefore, all analyses conducted on this issue help to test specific indicators and ways of measuring issues pertaining to fair and transparent competition along the supply chain. PSILCA provides four impact categories to analyze the stakeholder group of value chain actors:

- Anti-competitive behavior or violation of anti-trust and monopoly legislation,
- Active involvement of enterprises in corruption and bribery,
- Public sector corruption,
- Social responsibility along the supply chain.

Gathering data on issues like corruption and bribery is certainly challenging as a large number of hidden cases can be expected, which is an issue that needs to be kept in mind when conducting the analysis. In addition it should be mentioned that in "The Methodological Sheets for Subcategories in Social Life Cycle Assessment" (Benoît Norris et al., 2013), which provide guidance according to the UNEP/SETAC guidelines, different subcategories are given for the stakeholder group of value chain actors, e.g. Promoting Social Responsibility.

2.2. NdFeB permanent magnets description for S-LCA

Three process chains for rare earth permanent magnet production, which are characterized by the different ore origins and associated locations of further processing, are compared. The process chain data are based on existing or former mines and companies involved in providing the necessary RE metals and assembling the final permanent magnet. The use phase of the permanent magnets, e.g. in wind turbines, is not assessed in this paper. Therefore, only a cradle to gate scope is applied here. Due to their area of application, permanent magnets have various compositions. A typical NdFeB magnet used in wind turbines consists of approximately 65% iron, 32% RE metals, 2% cobalt, and 1% boron. Detailed technical information on the three mines can be found in Marx et al. (2018). Figs. 2 and 3 roughly summarize the three process chains, aggregated in the way they are used for the S-LCA. The process chain starts with three different mining sites. They are located in the United States (Mountain Pass, MP), in Australia (Mount Weld, MW) and in China (Bayan Obo, BO), representing 3%, 8% and 85% of world production in 2015, respectively (U.S. Geological Survey, 2016). In further production steps, the various rare earth oxides (REO) are made available (Fig. 2).

Beneficiation here describes the processes of crushing and milling the raw ore followed by flotation to produce REO concentrates. In the subsequent cracking process, chemicals are used to separate impurities and to transform the concentrates into RE chlorides and RE carbonates. The individual REs are then separated in elaborate solvent extraction processes using vast amounts of chemicals. Precipitation and calcination processes then follow to produce the separated REOs.

For the Mountain Pass case, beneficiation and separation also take place within the United States before the oxide is transported to China for reduction by electrolysis. For all three production routes, electrolysis is assumed to take place in China since currently the metals are predominantly produced here (Vogel and Friedrich, 2018). The final magnet fabrication in the US process chain is assumed to take place in Japan, as one of the few magnet producers outside China (Yang et al., 2017). The ore mined and beneficiated in Australia is transported to Malaysia for final processing of the RE oxide, which is also where final magnet production takes place after the metal returns from electrolysis in China. The Bayan Obo processes take place solely within China since all required facilities can be found there.

In addition to neodymium and praseodymium, the production of rare earth permanent magnets requires dysprosium (Fig. 3). For neodymium and praseodymium, the same process chains

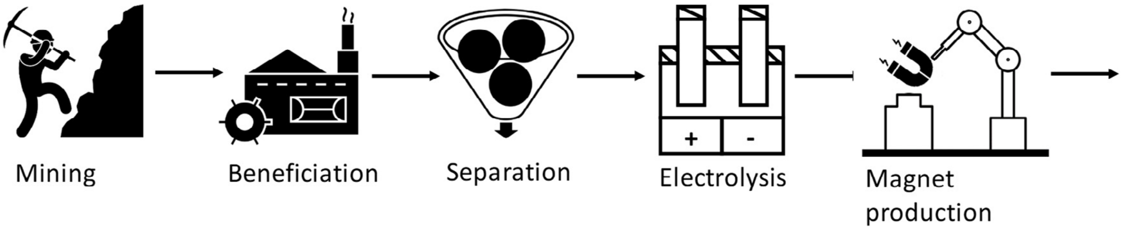

Fig. 2. Schematic representation of permanent magnet production steps.
Source: Icons from (Noun Project, 2019).
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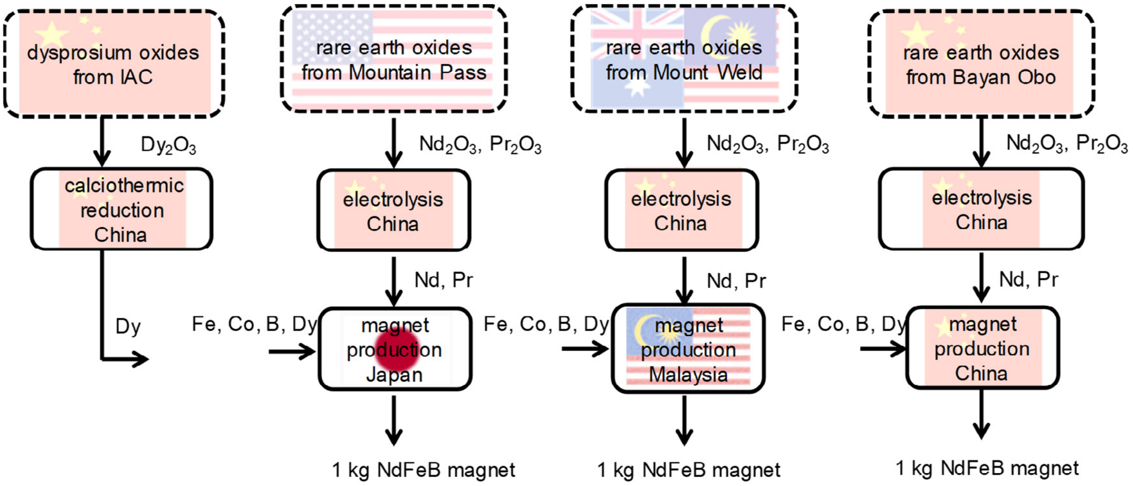

Fig. 3. Schematic representation of the three process chains.
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are assumed as both are produced from the same ore mixtures found at the three mines. However, the dysprosium for all three process chains is assumed to be produced from ion adsorption clays (IACs) in China, as this is where 80% (Yang et al., 2013) of current world production takes place. Therefore, all three process chains entail dysprosium from China, which is added during final magnet production. As PSILCA identifies risk on a country and sector level, the location of production steps is of vital importance to the results.

The prices for converting physical values into monetary values for input into PSILCA are determined using world market prices and global purchasing platforms such as Alibaba.com. The detailed price information and sources can be found in the Supplementary Information. Given that publicly available price information is subject to uncertainties, the results need to be understood with the necessary reservations.

The functional unit for the analysis is 1 kg of NdFeB magnet composed of 65% iron, 32% RE metals, 2% cobalt, and 1% boron. As RE metals 26% neodymium, 5% praseodymium and 1% dysprosium are used. The cut-off criterion used in PSILCA for this assessment is 1E-9, which means that the results include all the sectors up to the ninth level of upstream processes.

3. Results & discussion

The results section is divided into five parts, each one looking in detail at a different aspect of the results for value chain actors. Firstly, an overview of the results for all stakeholders is given. Then the analysis focuses on the different impact categories and specifically identifies salient issues for value chain actors while keeping in mind the quality of underlying data. The third set of results analyzes the most vulnerable production phase in each supply chain, while the fourth looks at the results from a sectoral perspective to identify the sectors that contribute to social risks. As a last final step, a geographic analysis is performed to show the overall contribution of all the sectors in a country to the total risk.

3.1. Result overview

As mentioned above, PSILCA provides 49 quantitative and semi-quantitative impact categories for all stakeholders. Within the Social Life Cycle Impact Assessment (S-LCIA) some of the primarily environmental categories such as DALYs and pollution are excluded, which leads to 42 social impact categories. Table 3 gives an overview of the results where the worst supply chain for each impact category is highlighted. When interpreting these results it is important to, firstly, keep in mind that there is a great difference in data availability and reliability between the impact categories and, secondly, that the absolute medium risk hours are not measured on a particular scale but only become meaningful in comparison within one impact category.

Overall, the Mount Weld supply chain entails the highest number of impact categories with the highest medium risk hours across all categories followed by the Bayan Obo and the Mountain Pass chains. With respect to 22 of 42 impact categories, the Mount Weld chain indicates the highest level of risk, for 17 impact categories the highest risk level is found in the Bayan Obo chain while the Mountain Pass chain only performs worst for three impact categories.

The analysis also shows one impact category that is measured in terms of opportunity instead of risk. Contribution to economic development refers to the “monetary contribution to a country’s GDP” (Eisfeldt and Ciroth, 2017) per sector. While the analysis reveals several high social risks within the Bayan Obo and Mount Weld magnet production, this impact also indicates a high level of opportunity to contribute to economic development, at least for Bayan Obo.

For some impact categories such as association and bargaining rights, public sector corruption, trade unionism, or social security expenditures the assessed risks vary widely between the process chains. The greatest spread is found for the impact category of international migrant workers. The Mount Weld chain has values more than 20 times higher than the other two chains. While many impact categories show clear preferences for one or the other process chain, some with rather small risk figures cannot be distinguished, such as men in the sectoral labor force or unemployment. The reason why there is a large or small difference between the processes chains depends to a large extent on the process chain and the impact category. Therefore, no general conclusion can be drawn.

In terms of risk per stakeholder group, value chain actors can be identified as the most vulnerable group across the three cases because it has the highest average indicator values of all stakeholder groups. This result additionally supports the choice of stakeholder category made before the analysis as this under-researched group is also confronted with the highest risks.

3.2. Impact Categories

Fig. 4 presents an overview of the results for the four impact categories describing the stakeholder group value of chain actors. The ranking between the three process chains is different for each impact category. Bayan Obo displays the highest risks for public sector corruption and anti-competitive behavior or violation of anti-trust and monopoly legislation. Active involvement of enterprises in corruption and bribery has the highest risks in the Mountain Pass chain. Mount Weld shows the highest risks in social responsibility along the supply chain.

Overall, it can be seen that public sector corruption is the impact category involving the highest level of risk; however, due to different levels of data availability and reliability the four impact categories cannot be considered in a comparative manner but have to be analyzed separately.

For example, one might wonder why public sector corruption yields such high medium risk hours whereas the impact category active involvement of enterprises in corruption and bribery displays only small numbers. The reason for this discrepancy can be found in the underlying data. The impact category public sector corruption provides information on 167 countries in PSILCA, gathered from the annual Transparency International Corruption Index (Transparency International, 2019). Since corruption is very difficult to measure, the index combines different data sources, thereby providing the most reliable data source on this issue worldwide. For the category referring to corruption and bribery in enterprises data is only available for OECD countries as well as Argentina, Brazil, Bulgaria, Colombia, Latvia, Russia and South Africa (Eisfeldt and Ciroth, 2017), which means that for a large number of countries the risk assessment in PSILCA is ‘no data’. As can be seen in Table 2 ‘no data’ is treated as equivalent to low risk in the LCIA phase, which may be an explanation for the fact that enterprises are portrayed as being much less corrupt than the public sector since, for example, no data for China and Malaysia are available. This is not to say that public sector corruption is not an issue but that results need to be interpreted within the context of the underlying data in order to draw meaningful conclusions about the impact categories.

The second highest level of risk is found for the impact category social responsibility along the supply chain. This category focuses on the extent to which social responsibility is taken seriously by companies in a specific sector. The membership of the UN Global Compact Initiative, an association that binds

Table 3
Overview of all impact categories for all stakeholders in medium risk hours, worst value of each impact category shown in bold.

Stakeholder	Impact category	Mount Weld	Mountain Pass	Bayan Obo
Workers	Child labor, female	14.9	5.9	**31.1**
	Child labor, male	15.1	6.1	**31.2**
	Child labor, total	15.0	6.0	**31.2**
	Frequency of forced labor	**2.6**	1.1	1.0
	Goods produced by forced labor	5.2	1.4	**7.4**
	Trafficking in persons	16.0	6.6	**32.6**
	Fair salary	27.2	20.5	**81.6**
	Weekly hours of work per employee	1.0	0.4	0.9
	Gender wage gap	**24.1**	16.7	9.5
	Men in the sectoral labor force	0.1	0.1	0.1
	Women in the sectoral labor force	**5.2**	2.6	2.6
	Non-fatal accidents	**5.3**	3.6	4.4
	Fatal accidents	**1.4**	1.2	1.0
	Safety measures	36.2	13.0	**52.2**
	Workers affected by natural disasters	15.2	5.6	**30.8**
	Social security expenditures	**111.7**	19.9	43.9
	Violations of employment laws and regulations	7.8	5.1	**22.0**
	Trade unionism	**115.8**	42.8	26.2
	Association and bargaining rights	83.8	55.8	**329.7**
Value chain actors	Public sector corruption	172.4	69.3	**320.9**
	Active involvement of enterprises in corruption and bribery	2.2	**5.3**	2.1
	Anti-competitive behavior or violation of anti-trust and monopoly legislation	2.4	3.7	**6.4**
	Social responsibility along the supply chain	**123.0**	**48.6**	105.7
Society	Contribution to economic development	−5.7	**−4.2**	−20.9
	Education	19.1	9.4	**33.0**
	Illiteracy, female	**26.1**	12.3	14.3
	Illiteracy, male	**23.7**	11.3	10.6
	Illiteracy, total	**24.6**	11.4	10.9
	Youth illiteracy, female	**3.7**	1.7	2.1
	Youth illiteracy, male	**4.4**	2.0	2.3
	Youth illiteracy, total	**4.4**	2.0	2.4
	Health expenditure	**51.9**	16.6	23.1
	Life expectancy at birth	**1.3**	1.0	0.8
Local communities	Certified environmental management system	96.2	59.5	**176.2**
	Indigenous rights	7.8	**13.3**	8.4
	Drinking water coverage	**7.7**	4.6	5.2
	Sanitation coverage	103.7	66.7	**318.3**
	Unemployment	1.2	1.0	**1.3**
	International migrant stock	**7.8**	3.3	3.0
	International migrant workers (in the sector/ site)	**50.0**	2.3	2.5
	Net migration	**0.5**	0.1	0.1
Consumers	Presence of business practices deceptive or unfair to consumers	2.5	0.7	**2.8**

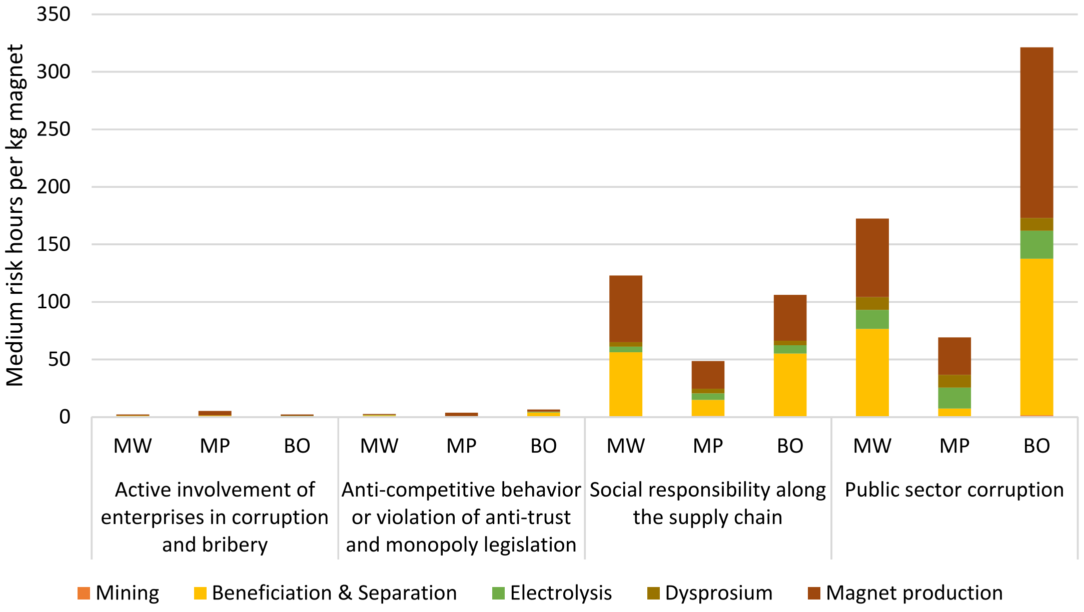

Fig. 4. Overview of results for stakeholder group of value chain actors for the production of REO magnets.

participating companies to align their strategies to ten principles addressing human rights, labor standards, the environment and corruption, is used as a proxy (UN Global Compact, 2018). For the risk assessment in PSILCA, country-specific-sectors that are found not to have any company represented in the UN Global Compact Initiative are assessed as very high risk. While participation in the initiative can certainly improve the visibility of a company as being socially responsible a membership is also associated with time and personnel commitment, which is particularly difficult to realize in sectors that are characterized by small- and medium-sized enterprises without a structure that allows for such initiatives. Nevertheless, this impact category provides a good indication of the sectors that need to improve on social responsibility and encourages ideas about how to improve the quantitative assessment of such corporate activities.

The impact category anti-competitive behavior or violation of anti-trust and monopoly legislation refers to any kind of anti-competitive behavior such as price fixing. Such behavior indicates a distortion of the free market and potentially excludes certain companies from competition. Data on such behavior is rather difficult to gather as reporting and prosecution of these cases differs greatly between countries. The data used in PSILCA are based on enforcement cases recorded in the US, which are sorted by sector. The assumption is that "occurrence and frequency of anti-competitive behavior and unfair business practices are similar for the same industry sector worldwide" (Eisfeldt and Ciroth, 2017), which means that US data are extrapolated to industry sectors around the world. Whether this is an adequate representation of reality, is debatable. Therefore, this impact category can be understood as a starting point for a discussion of how to measure anti-competitive behavior and implement data in a global database.

Even though the assessment of unfair business practices and companies' market-distorting activities proves difficult to measure, the importance of such aspects in the sustainability assessment of a product or processes remains undisputed. PSILCA provides a first conceptualization of what kind of indicators are important in such assessments and opens the floor for further discussion and revision.

In comparison with LCA, the Mountain Pass process chain shows better results in terms of environmental impacts than Bayan Obo and Mount Weld except for particulate matter (Marx et al., 2018). With regard to social impacts, the picture is more differentiated. For example, for the impact category public sector corruption the order is the same as for LCA. Bayan Obo performs worst, followed by Mount Weld and Mountain Pass. However, for social responsibility along the supply chain Mount Weld performs worst, followed by Bayan Obo and Mountain Pass. There is even an impact category (active involvement of enterprises in corruption and bribery) where Mountain Pass scores worst, followed by Mount Weld and Bayan Obo. Another common feature between LCA and S-LCA is that many medium risk hours are often due to beneficiation, which again is caused by the use of chemicals. In contrast to LCA, the share of magnet production in the total medium risk hours in S-LCA is quite high. In LCA, the share of magnet production amounts to less than 5% for most environmental impacts. The share of mining activities is low in both LCA and S-LCA.

3.3. Contribution of production phases

As indicated in the previous section, data for the four impact categories describing value chain actors differ widely. These differences can be investigated further by taking a closer look into the production phases and sectoral analysis.

Fig. 5 shows the medium risk hours for public sector corruption divided into the five production phases necessary to produce the magnet. The first phase solely refers to the process of mining the raw ore for the three mining sites. The beneficiation & separation phase includes a number of processes, which are aggregated for ease of understanding. The third phase is reduction of the rare earth oxide by electrolysis, which takes place in China in all three cases. In the fifth phase, the final magnet is assembled. Dysprosium production from mining to metal production in China is aggregated in a separate process and added during the magnet production. It is shown separately because it is identical for all three process chains and facilitates understanding of the differences due to the neodymium and praseodymium production phase.

A first observation from Fig. 5 is that the production phases show a differentiated picture for the three cases. Whereas Bayan Obo and Mountain Pass involve most risks during magnet production (47% and 46%), Mount Weld has the highest risks due to beneficiation & separation (44%). Dysprosium production is at almost the same low level for all routes. The only minor differences are caused by the different transportation processes of dysprosium to the magnet production sites in China, Malaysia and Japan, respectively. However, due to the lower total impact in Mountain Pass the dysprosium production has a greater influence when considering the share contributed (16% compared to 6% and 3% for Mount Weld and Bayan Obo, respectively). The production phase of mining shows the lowest level of risk in all impact

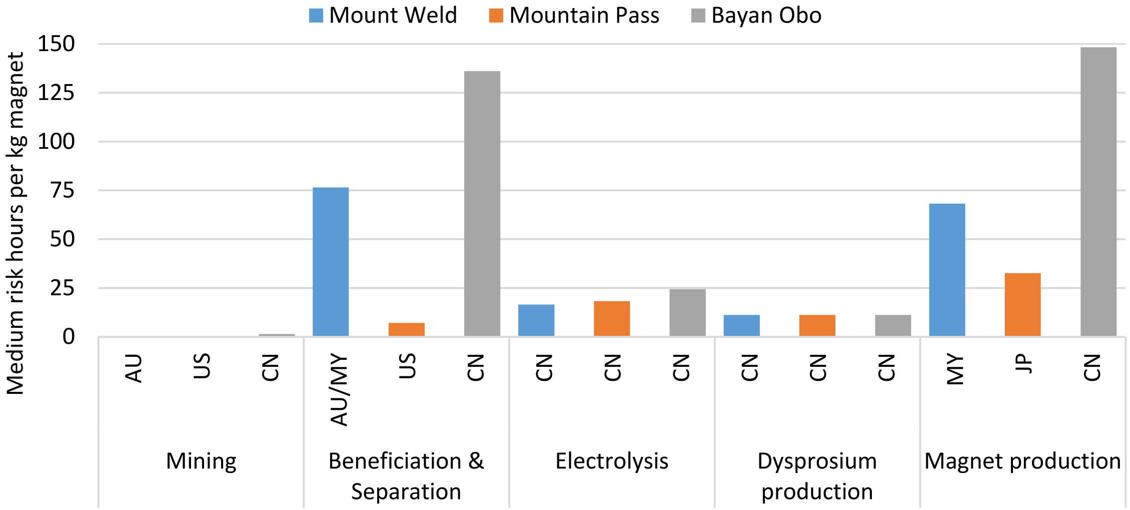

Fig. 5. Medium risk hours per production phase for public sector corruption for the production of REO magnets.

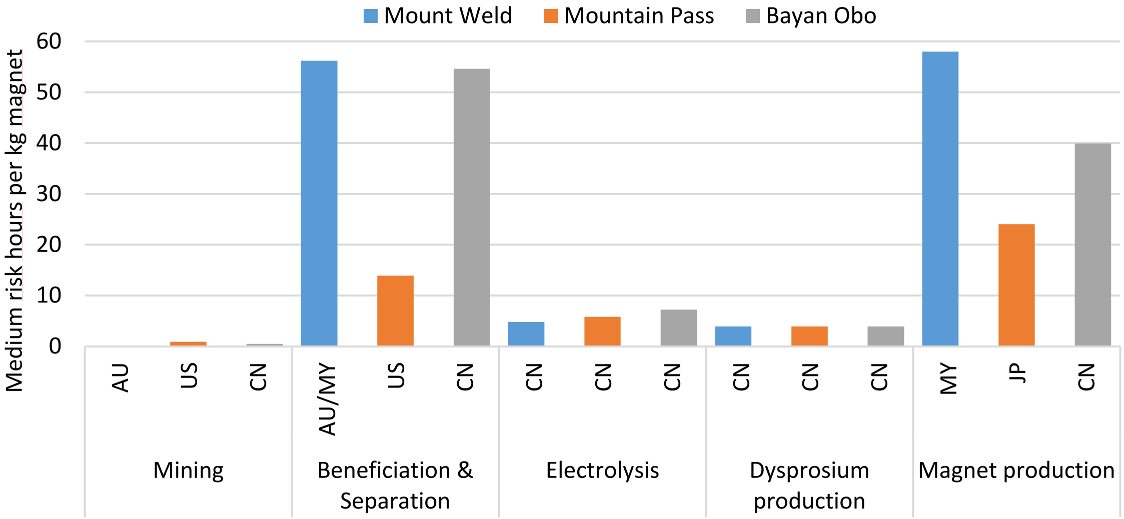

Fig. 6. Medium risk hours per production phase for social responsibility along the supply chain for the production of REO magnets.

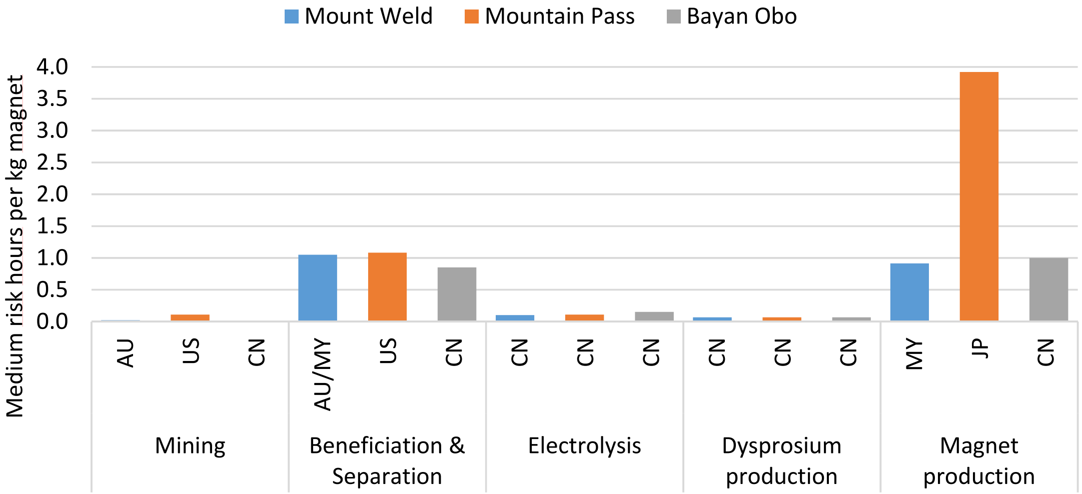

Fig. 7. Medium risk hours per production phase for active involvement of enterprises in corruption and bribery for the production of REO magnets.

categories (<0.5%). As mentioned in Section 2.1, the different production phases are not weighted in terms of worker hours in this study. Unfortunately, it was not possible to obtain reliable information for all three mines, which means that only the input sectors are measured in terms of risk in this phase. However, even though mining is highly mechanized it still requires a great deal of work. Consequently, higher amounts of inputs in the other three phases are responsible for the higher level of risk. All of the results need to be understood in this context. Overall, the Bayan Obo chain shows the highest risks for public corruption being nearly twice as great as Mount Weld and about five times higher than Mountain Pass.

Fig. 6 shows the highest risk levels for the Mount Weld chain with respect to social responsibility along the supply chain. They originate mainly from magnet production and beneficiation & separation for Mount Weld (47% and 45%) but also for Bayan Obo, although slightly better and in reverse order (51% and 38%). Here the absolute values for Mountain Pass and Bayan Obo do not vary as prominently as for public sector corruption. The risk values are much smaller for active involvement of enterprises in corruption and bribery (Fig. 7) and anti-competitive behavior or violation of anti-trust and monopoly legislation (Fig. 8). The risks in the Mountain Pass chain become more dominant, especially during magnet production. These social impacts mainly originate from the boron content of the magnet. The OECD puts the involvement of Japanese companies in the sector other non-metallic ores (sector for boron production in Japan) at 19% (Eisfeldt and Ciroth, 2017) leading to a very high risk for this sector. The same is true for the presence of anti-competitive behavior or violation of anti-trust and monopoly registration, while the risk for a similar sector in Malaysia is characterized as low. The risks for anti-competitive behavior or violation of anti-trust and monopoly legislation are also significant for the beneficiation & separation phase at Bayan Obo. For example, anti-competitive behavior impacts in China are in general twice as high as in Australia and Malaysia (Mount Weld production chain). As mentioned the lack of data available for China and Malaysia in the active involvement of enterprises in corruption and bribery and the way in which this missing data is treated (comparable to low risks) plays a significant role and may lead to an underestimation of the Bayan Obo and Mount Weld process chains for this impact category.

3.4. Sectoral level

The beneficiation & separation processes generally involve a large amount of chemicals. In order to identify whether the chemical sector is also responsible for the associated risks in these processes the following section will identify the input sector from

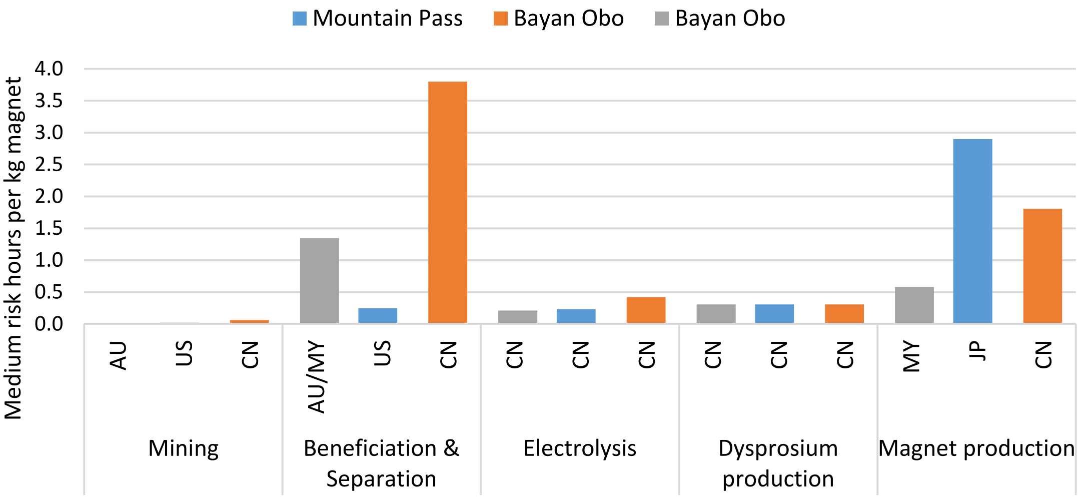

Fig. 8. Medium risk hours per production phase for anti-competitive behavior or violation of anti-trust and monopoly legislation for the production of REO magnets.

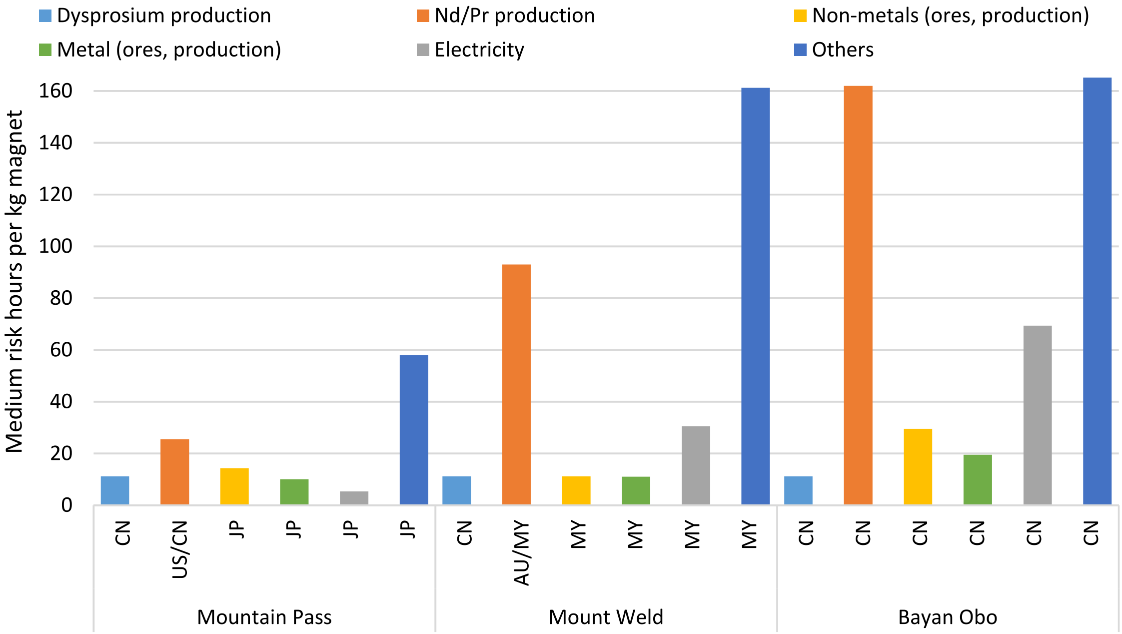

Fig. 9. Share of medium risk hours per sector for public sector corruption in the entire supply chain.

which these medium risk hours originate. This sectoral analysis is also necessary to identify the reasons why magnet production shows such significant risk levels.

The sectoral analysis examines the medium risk hours per sector contributing to a particular impact category. Public sector corruption was chosen as an example, since data quality is higher compared to the other impacts.

Fig. 9 shows the share of risk per (sector) input in the magnet production process in relation to the three supply chains of neodymium/praseodymium. In addition to neodymium/praseodymium production, magnet production requires inputs mainly from the metal and non-metal, i.e. mineral, sectors as well as electricity. The input from the mineral sector refers to boron oxide as an input for the magnet, while the metal ores sector describes the iron and cobalt input. As mentioned earlier (Section 2.2) dysprosium is also needed in order to produce the final magnet. Neodymium/praseodymium production is shown to contribute the major proportion of risk to public sector corruption for all chains, followed by electricity for the Mount Weld and Bayan Obo chains. This figure also illustrates very well the different risk levels of the analyzed countries. While in Japan (location of magnet production for the Mountain Pass chain) electricity is more expensive than in the other countries (Supplementary Information), the risk results show the lowest impacts due to electricity in the Mountain Pass process chain. Japan has a lower risk level for public sector corruption than Malaysia and China (medium risk in Japan, very high risk China). For the metal and mineral inputs, the same prices are assumed in all three countries. The results, however, show a much higher risk for the Bayan Obo production chain.

In the sector-level analysis (Fig. 10), the relevant sectors for public sector corruption are identified as comprising besides magnet production also the beneficiation & separation phase due to neodymium/praseodymium production.

Fig. 10 shows that most of the social risk related to the beneficiation & separation phase stems from the chemical sectors. Here the production route from Bayan Obo shows the highest risk, in most cases followed by Mount Weld except for fossil fuels. These differences arise for several reasons. Firstly, the different ore types require different processing technologies and different

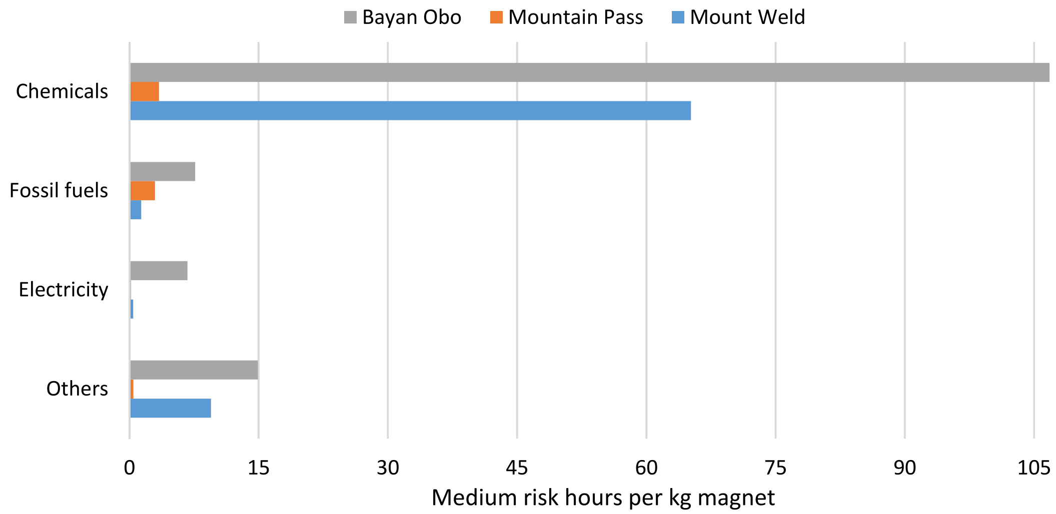

Fig. 10. Medium risk hours per sector for public sector corruption in the beneficiation & separation phase.

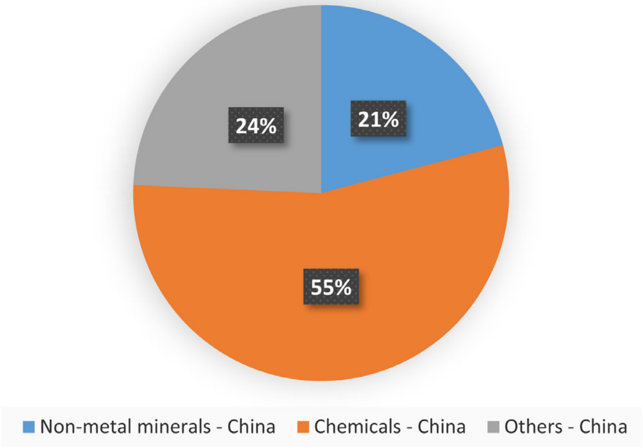

Fig. 11. Share of public sector corruption medium risk hours per sector for dysprosium production.

amounts of chemicals, secondly the efficiencies of the processes vary from region to region and thirdly the prices in the regions are not the same.

Dysprosium production plays an important part in all three process chains. It is modeled for every process chain in the same way from a Chinese IAC source. The processes differ from the neodymium/praseodymium production routes with respect to the mining and beneficiation processes. In contrast to the two elements mentioned above, dysprosium is obtained by in situ leaching. Because of the higher share of heavy rare earth elements in the IACs, the separation chemicals are different as well. This mainly requires inputs from the chemical industry and the minerals sector.

Fig. 11 shows that the risk for public sector corruption in dysprosium production comes from these sectors in China. The non-metal minerals input in dysprosium production refers to the additives used in the drilling process to extract IACs by in situ leaching. The chemicals sector includes mostly ammonium sulfate as a leaching agent during in situ leaching and hydrochloric acid, which is used for further beneficiation processes. Additionally chemicals are used for solvent extraction to produce the rare earth oxides. This analysis underlines the strong impact of chemicals from the beneficiation & separation phase for dysprosium, which is in line with neodymium/praseodymium production.

In order to arrive at specific recommendations of whether or not one production location and its suppliers is better than another in terms of social risks a hotspot analysis such as conducted here provides a good overview of the salient issues to be addressed and the sectors to be targeted. However, more information on particular suppliers and networks would be needed to conduct a more precise analysis by, for instance adjusting the risk levels for certain sectors. If, for example, a company knows that a supplier has taken effective measures to combat corruption the risk level for this input sector could be adjusted manually in PSILCA.

3.5. Geographic analysis

The geographic analysis portrays the risks within countries which are part of the system investigated either according to direct production sites or due to international trade in supply chains. Fig. 12 shows the contributions of countries to public sector corruption. China plays an important role across all three cases. Given that the electrolysis process and dysprosium process in all three cases take place in China this result is not very surprising. As for the Mount Weld and the Mountain Pass chains the points of production in Australia, the US, and Japan are not displayed as their contribution is smaller than 1% to the total amount of public sector corruption risk. Malaysia, however, has production sites for separation and magnet production in the Mount Weld process chain and is the most important country in this production chain. Keeping in mind the technology description in Section 2.2 the role of India for all three process chains is somewhat puzzling as no Indian sectors directly feed into the processes. However, the role of India in the global market combined with the I/O-model on which PSILCA is based provides part of the explanation. The high volume of trade that takes place in India ensures that in almost any given process around the world upstream processes in India will play a role. This trade effect can also account for some of the risks associated with China even though this is more difficult to argue in this particular study.

The picture changes if the impact category of social responsibility along the supply chain is taken into consideration (Fig. 13).

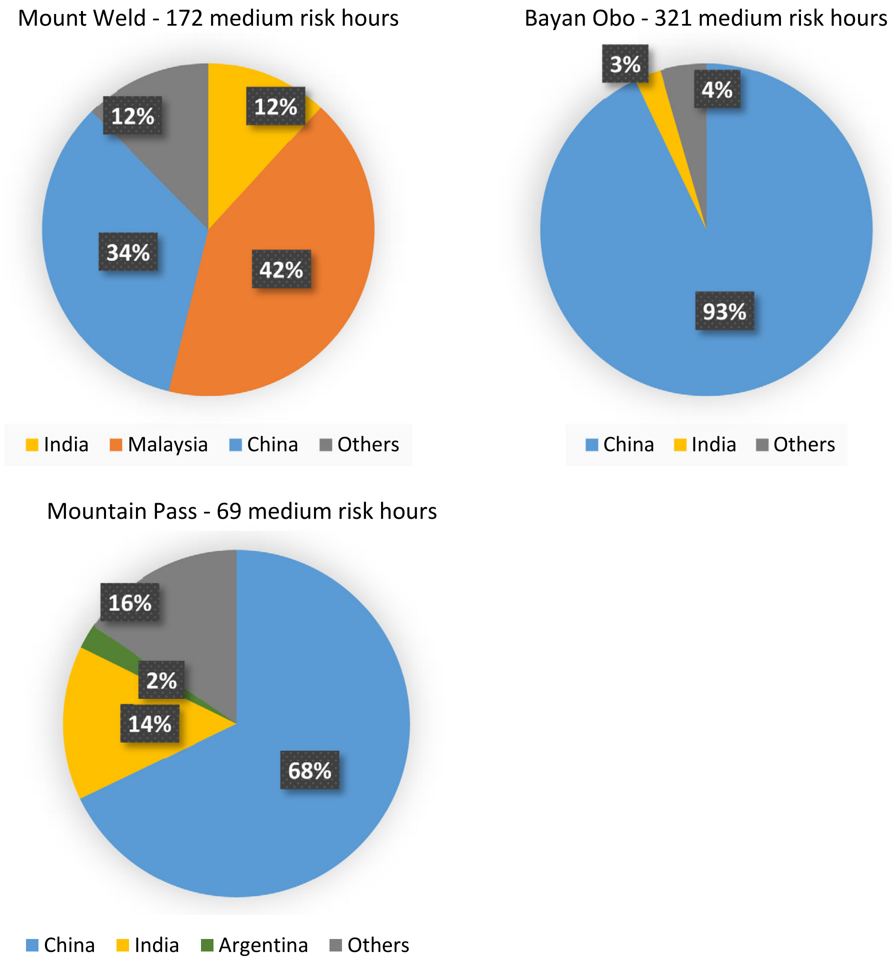

Fig. 12. Contribution of medium risk hours per country to public sector corruption.

While China still plays a substantial role, especially the production countries now become more visible. In addition, the percentage of other closely involved countries increases. In particular, the US-based Mountain Pass process chain has high percentage due to the strong international links of the US economy. As previously mentioned, the data reliability is somewhat limited because non-signatory sectors to the UN Global Compact are given a high risk label.

4. Conclusion

The analysis with the PSILCA database allows a specific assessment of social hotspots along the three supply chains thus identifying the most vulnerable process phases and sectors contributing to social risks. Looking at all social impact categories for all stakeholders, the US processing chain is the clear winner. The chains from Mount Weld and Bayan Obo show a comparable share in impact categories with the highest risks. While Mount Weld has the most indicators with the highest social impacts, for the Bayan Obo process chain some indicators show very poor results. However, when focusing on the stakeholder group of value chain actors, represented in four impact categories, the ranking between all three chains varies. For the two impact categories with the most reliable data, public sector corruption and social responsibility along the supply chain, Bayan Obo and Mount Weld, respectively, perform worst. Only for the impact category of the active involvement of enterprises in corruption and bribery, which is not so representative, does Mountain Pass show the highest risks.

The results can serve as a basis for further investigations. The stakeholder group of value chain actors is especially important because they can actually change something in order to minimize the social impacts by complying with standards, thus improving the social situation in their production plant and putting pressure on other suppliers. Magnet production and beneficiation & separation are the phases of the process chains with the highest contribution. A particular company in those phases of the process chain could use the results to test their own supply chain, contact their suppliers and collect primary data with which the generic assessment can be modified. As the results show, the chemicals sector is problematic with respect to public sector corruption during beneficiation & separation, particularly in China. Responsible sourcing of chemicals from companies that ensure corruption-free supply chains could be one possible way to decrease risks in this regard.

The results for magnet production reveal additional information. While the amounts of inputs are assumed the same in all three magnet production countries, the risks of public sector corruption vary. Even the prices for metals and minerals are considered the same, since country specific values are not available. The differences in risks are therefore solely representing the different impacts in these countries. For the electricity supply, the country with the highest prices (Japan) displays very low risk of public sector corruption and therefore contributes little to the overall risk.

One way to improve the results of this study would be to use actual prices traded between the companies involved as input for PSILCA. This step would provide a more reliable analysis

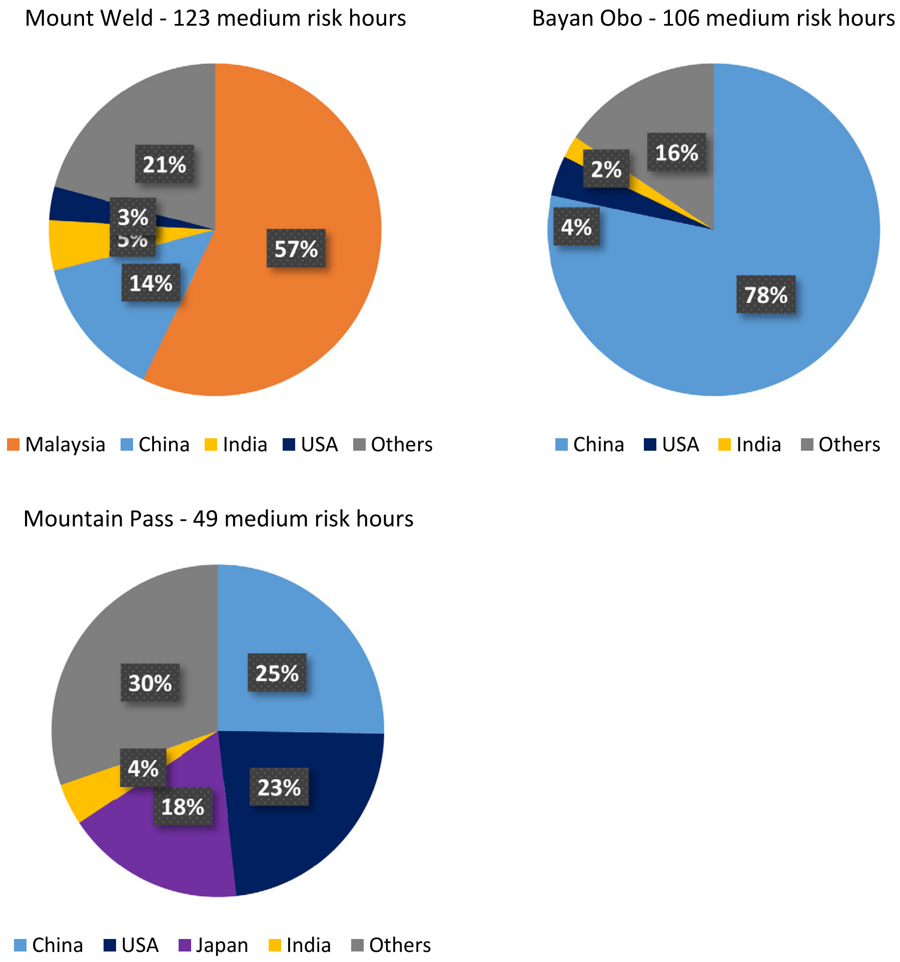

Fig. 13. Contribution of medium risk hours per country to social responsibility along the supply chain.

and possibly change the social risk evaluation. Furthermore, if a dedicated process chain with information about the suppliers is analyzed also the risk assessment in PSILCA should be adapted, for example if a supplier has undertaken certain measures to prevent bribery, in order to obtain a more realistic picture of the social situation due to this specific process chain.

With respect to the geographic analysis, it depends on the impact category whether the actual production processes along the process chain contribute significantly to the risks, or rather the supply chains. The risk for public sector corruption, for example, arises to a great extend in Chinese sectors for all three chains considered. Social responsibility along the supply chain, however, is a topic in the producing countries as well. Nevertheless, this does not necessarily imply that production should not take place there. If a thought experiment is employed where all production along the Mount Weld supply chain, especially those processes taking place in Malaysia, were switched to other countries due to high social risks it has to be recognized that such actions would most likely have more negative than positive consequences. While the magnet itself would be considered more sustainable, local value chain actors involved in magnet production in Malaysia would lose their businesses with corresponding consequences for their employees and subsequently for the local community.

As mentioned at the beginning of this study, social sustainability means that new technologies should not harm people's living conditions and should only improve them in a way that does not have detrimental effects on social structures. In this study, issues of corruption, bribery and fair competition have been evaluated, which could be argued to have adverse effects on social structures. Consequently, improving these issues can also be understood as increasing social sustainability.

Overall, S-LCA is still a rather young concept and methods and data availability are constantly developing. One big issue is the classification of impact categories with no data as comparable to low risk. In this assessment, this probably leads to an underestimation of the risk of corruption and bribery in China and Malaysia. The best solution would be to fill the data gaps. If this is not possible, a classification of no as at least medium risk seems appropriate. Nevertheless, the results give a good indication of the social risks along the supply chains of permanent magnet production and reveal room for improvement in the methodology.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.spc.2019.07.006.

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