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Koese, J.M.; Blanco Rocha, C.F.; Vert, V.B.; Vijver, M.G.

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A social life cycle assessment of vanadium redox flow and lithium-ion batteries for energy storage

Maarten Koese[1] | Carlos F. Blanco[1] | Vicente B. Vert[2] | Martina G. Vijver[1]

[1]Institute of Environmental Sciences (CML), Leiden University, Leiden, The Netherlands

[2]Construction and Renewable Energies Group, AIMPLAS, Technological Institute of Plastics, Valencia, Spain

Correspondence
Maarten Koese, P.O. Box 9518, 2300 RA Leiden.
Email: j.m.koese@cml.leidenuniv.nl

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Abstract

Battery energy storage systems (BESS) are expected to fulfill a crucial role in the renewable energy systems of the future. Within current regulatory frameworks, assessing the sustainability as well as the social risks for BESS should be considered. In this research we conducted a social life cycle assessment (S-LCA) of two BESS: the vanadium redox flow battery (VRFB) and the lithium-ion battery (LIB). The S-LCA was conducted based on the guidelines set by UNEP/SETAC and using the PSILCA v.3 database. It was found that most social risks related to the life cycle of the batteries are associated with the raw material extraction stage, while sectors related to chemicals also entail considerable risks. Workers are the stakeholder group affected most. These results apply to supply chains located in both China and Germany, but risks were lower for similar supply chains in Germany. An LIB with a nickel manganese cobalt oxide cathode is associated with considerably larger risks compared to a LIB with lithium manganese oxide cathode. For a VRFB life cycle with an increased vanadium price, the social risks were higher than those of the VRFB supply chain with a regular vanadium price. Our paper shows that S-LCA through the PSILCA database can provide interesting insights into the potential social risks associated with a certain product's life cycle. Generalizations of the results are not recommended, and one should be careful with assessments for technologies that have not yet matured due to the cost sensitivity of the methodology.

KEYWORDS
energy storage, industrial ecology, PSILCA, social life cycle assessment, socially informed decisions, sustainability assessment

1 | INTRODUCTION

Energy storage systems (ESS) are expected to play a key role in the transition to renewable energy (IEA, 2021a) as the variability of electricity supply increases due to the expanding contribution of renewable energy technologies in the energy mix. This leads to a growing need for large stationary energy storage possibilities (Denholm & Hand, 2011). Batteries are one of the possibilities for energy storage expected to fulfill a crucial role in the renewable energy system of the future (Dunn et al., 2011). Battery energy storage systems (BESS) lead to enhanced stability, reliability, security, and efficiency of the energy system (Gür, 2018; Mohamad et al., 2018). To safeguard a resilient supply chain for BESS in the future, sustainability of its lifecycle should receive attention. This includes the availability of critical materials (IEA, 2021b; Sprecher & Kleijn, 2021) and environmental sustainability of the BESS life cycle (Sadhukhan & Christensen, 2021; Weber et al., 2018), but social sustainability should also receive attention. The production of battery materials is often associated with detrimental social impacts (Amnesty International, 2016; Camacho, 2012; Liu & Agusdinata, 2020). Social factors are increasingly affecting critical material supply, having a larger influence on material availability than material reserves (Jowitt et al., 2020). However, studies considering the potential social risks or benefits related to BESS from a life cycle perspective are lacking. This paper addresses this gap by conducting a social life cycle assessment (S-LCA) on two different BESS, based on the S-LCA guidelines set by UNEP/SETAC (2020) and using the PSILCA (Product Social Impact Life Cycle Assessment) v.3 database developed by GreenDelta (Ciroth & Eisfeldt, 2016; Maister et al., 2020). The selected types of BESS, namely the vanadium redox flow battery (VRFB) and the lithium-ion battery (LIB), are considered in light of their potential social impacts on workers, local communities, and society. LIB are currently the most used BESS, while RFBs, with VRFB being the most mature, are promising emerging technologies (Dieterle et al., 2022; IEA, 2020). The workers, local communities, and society stakeholder groups are chosen because the supply chain is expected to mainly affect these stakeholders and these categories are covered most comprehensively in the PSILCA database (Sureau et al., 2018).

Increased attention for S-LCA can help address social harm in value chains of technologies that are otherwise environmentally sustainable, hence limiting burden shifting from environmental to social sustainability. For example, Muller et al. (2021) show that a shift from fossil fuel to renewable energy powered mining would entail environmental benefits but could lead to increased social risks at the same time. S-LCA can also contribute to avoiding the so-called "decarbonization divide," in which the diffusion of low-carbon transition technology harms communities upstream or downstream of the supply chain, in extracting the raw materials or handling the waste (Sovacool et al., 2020). The analysis by Thies et al. (2019) shows that this is indeed the case for LIB, of which the supply chain is associated with detrimental social impacts particularly at the raw material extraction stage. We are not aware of further studies describing the social impacts of BESS value chains from a life cycle perspective.

This paper aims to assess the potential social risk hotspots and benefits of the LIB and VRFB supply chains. Increased insight into the potential social impacts of these BESS can inform decision-makers when considering different technological alternatives and prioritizing innovation roadmaps. Moreover, taking the social aspects of the life cycle of these products into account corresponds with European Union (EU) goals for resilient and sustainable supply chains for batteries set in the EU Green Deal and EU Battery Regulation (European Commission, 2019, 2020). It also links to the Sustainable Development Goals of the UN (UN General Assembly, 2015), in which a holistic approach to sustainability is proposed. Furthermore, there is increasing attention for due diligence in policies such as the new EU Battery Regulation, which explicitly suggests S-LCA as a possible method (European Commission, 2020). Since the UNEP/SETAC S-LCA guidelines (2020) propose using a database to enhance feasibility of S-LCA studies, it is relevant to explore the value of conducting a comparative S-LCA with the help of the PSILCA database.

2 | METHODS

2.1 | Description of S-LCA and PSILCA database

The S-LCA approach builds on environmental life cycle assessment (E-LCA) and the ISO 14040 framework. In this paper, the PSILCA database (Ciroth & Eisfeldt, 2016; Maister et al., 2020) was used to conduct the S-LCA. This database, developed by GreenDelta in compliance with the UNEP/SETAC S-LCA guidelines, contains data for 19 subcategories and 65 qualitative and (semi-)quantitative indicators on social and environmental risks and impacts (UNEP/SETAC, 2020). It is based on the EORA multi-regional input/output database (Lenzen et al., 2012 , 2013), and covers around 15,000 country-specific industry sectors and commodities in 189 countries. The database incorporates social indicators for different stakeholder groups, that is, workers, local community, society, consumers, and value chain actors, measured at a certain point in time. Social risks are quantified by an activity variable, that is, worker hours, which describe the working time needed to produce 1 USD output of a sector. Social risks are translated and aggregated into medium-risk hours, specifying the observed risks related to producing 1 USD of output of a sector. These risk levels are scaled by the price of the input sectors, the amount of work hours of each process and the categorization factors, which then leads to the risk results per impact category (Di Noi et al., 2020). A more detailed description of the methods and implementation is provided in Supporting Information (Supporting Information S1, section 1).

The PSILCA database has been used in some S-LCA studies in the past, for example, on the production of polyethylene (Hannouf & Assefa, 2018), rare earth permanent magnets (Werker et al., 2019a), and hydrogen (Werker et al., 2019b); on raw material extraction (Di Noi et al., 2020; Muller et al., 2021); the clothing industry (Almanza & Corona, 2020; Martin & Herlaar, 2021); bioelectricity systems (Martin-Gamboa et al., 2020); mobility scenarios (Bouillass et al., 2021); the sustainability of a university (Bueno et al., 2021; Erauskin-Tolosa et al., 2021); and a waste water treatment plant (Serreli et al., 2021). The method has not yet been used to assess the social sustainability of batteries for energy storage, although Thies et al. (2019) have used another S-LCA database, the Social Hotspots Database (SHDB), to assess the supply chain of LIB.

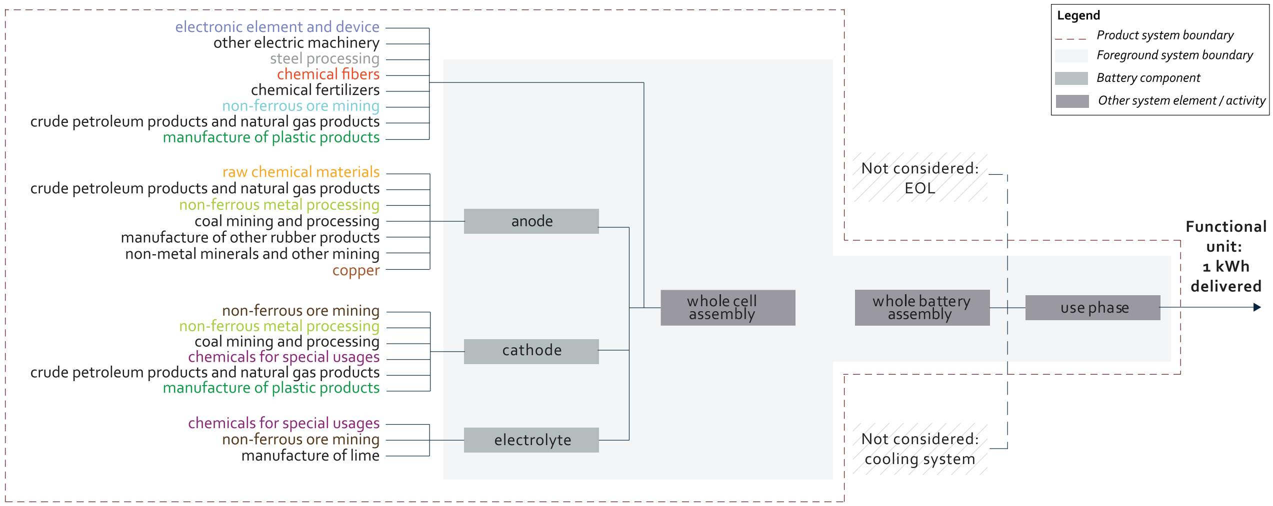

FIGURE 1 Product system flowchart of the lithium ion battery

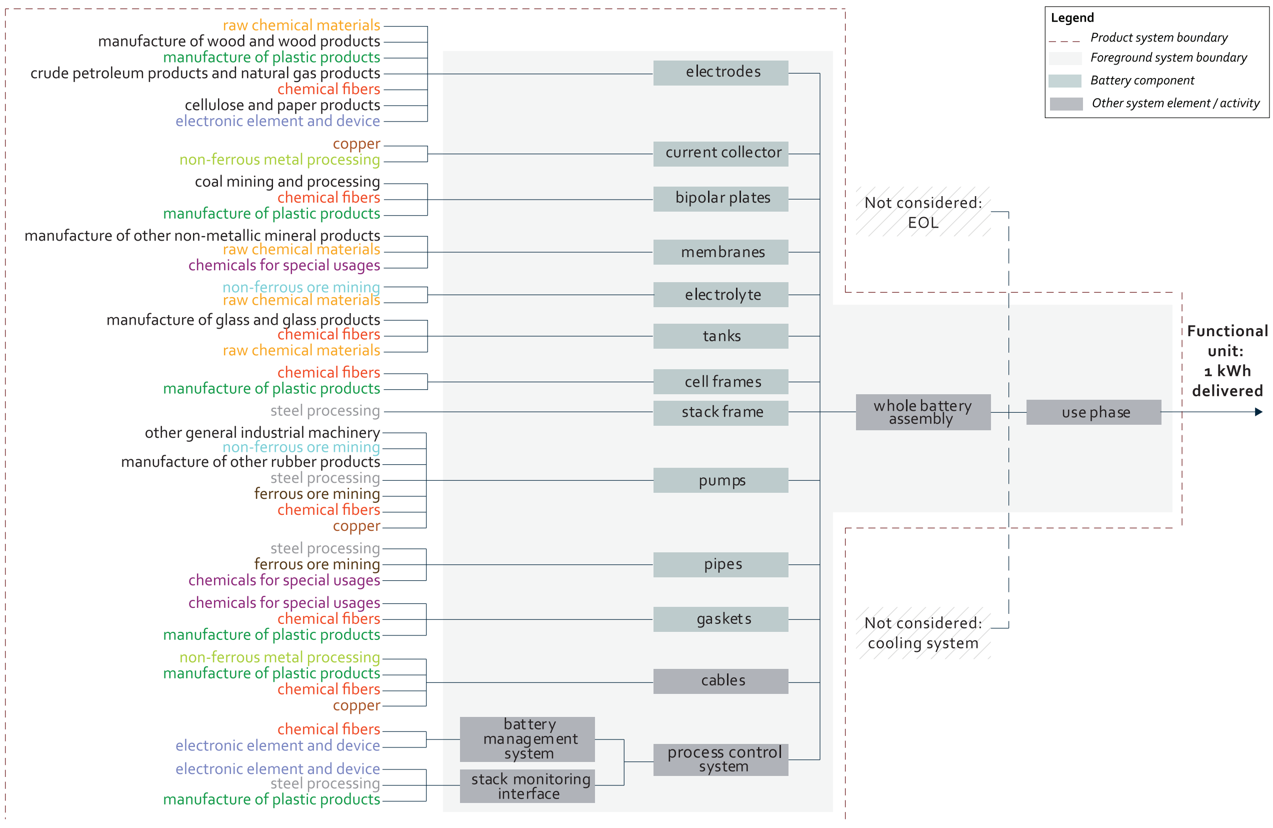

FIGURE 2 Product system flowchart of the vanadium redox-flow battery

2.2 | Goal and scope

The aim of this study is to assess the social risks related to two different stationary batteries for energy storage, the LIB (Figure 1) and the VRFB (Figure 2). The scope of the assessment is cradle-to-use, while potential risks introduced during end-of-life are discussed separately (see Section 4.1.2.). The functional unit is 1 kWh of electricity provided over the service life of the battery system (see Supporting Information S1, section 2 for calculation details). The focus is limited to the workers, local community, and society stakeholder groups. The value chain actor stakeholder group is excluded due to less reliable data, that is, corruption data extrapolated from the United States (Maister et al., 2020). Consumers are also excluded, since they are not expected to be affected.

2.3 | Life cycle inventory

For the VRFB, the life cycle inventory provided by Weber et al. (2018) was used as a starting point (see Supporting Information S1, section 4) while the inventory for the LIB was based on Sadhukhan and Christensen (2021) (see Supporting Information S1, section 5). Following the PSILCA method, these inventories (inputs and outputs of materials, products, and services) were translated to economic sectors by using the best available match in the PSILCA database in the most likely country of origin. For raw materials, a market mix approach was chosen based on USGS (2021) mineral commodities production data (e.g., in 2021, 66% of vanadium was produced in China, 17% in Russia, 8% in South Africa, and 6% in Brazil). The inputs and outputs from each sector were expressed as monetary values using cost data from ecoinvent (Wernet et al., 2016) and adjusting for inflation. Further details on calculations and values obtained are provided in Supporting Information S1, section 3.

2.4 | Sensitivity analyses

In addition to the reference LIB and VRFB batteries described above, three alternative configurations of the technologies and their supply chains were assessed to obtain additional insights. The first entails a shift in geographical location of the life cycle, the second a different material composition of the battery, and the third a cost increase of the material.

2.4.1 | Geographical location

Literature suggests that the geographical location of a battery supply chain may influence the social risks to a large extent (Thies et al., 2019). We thus analyzed the same product systems (except for raw material extraction) located in Germany instead of China since Germany is one of the pioneering markets for stationary BESS (Figgene, 2020). Moreover, the EU is actively trying to increase sustainability in batteries (European Commission, 2020), and a production process within the EU would increase control over battery sustainability. The EU is also actively supporting the production of strategic products within its borders (European Commission, 2022). With the green energy transition battery supply may also be considered strategic in the near future, prioritizing the need for battery production in the EU. It is therefore interesting to see how the social risks profile would shift with production in Germany, a country with very different production and working circumstances compared to China.

2.4.2 | LIB with nickel manganese cobalt oxide cathode

The LIB inventories we used in this paper (Sadhukhan & Christensen, 2021) considered lithium manganese oxide (LMO) cathodes. It has been found that LMO cathodes perform better environmentally than cobalt cathodes (Yin et al., 2019) and may also outperform nickel manganese cobalt oxide (NMC) cathodes from a social perspective due to the high social risks associated with cobalt (Amnesty International, 2016; WEF, 2019). However, lithium NMC cathodes are often used in LIB, currently dominating the market in electric vehicles (Zubi et al., 2018) and are a common choice for stationary applications as well (IRENA, 2017). Thus we investigate the change in risk profile with a switch to NMC111 cathode, which has a low nickel/cobalt ratio that safeguards stability and rate performance (Jung et al., 2017) and is currently dominant in practice (Dai et al., 2018). Supporting Information S1, section 5 contains more information about assumptions and the LCI of this cathode.

2.4.3 | VRFB with increased vanadium price

It is widely known that commodity prices can be extremely volatile (Pindyck, 2004). The price per kg of vanadium pentoxide (V_2O_5) is shown to vary between 5 and 10 USD within the same year (USGS, 2021). In the future, the general costs of the VRFB are expected to decline due to technological improvements (Viswanathan et al., 2014), while the price of vanadium will most likely increase due to increasing demand and supply risks (Ciotola et al., 2021; Gilligan & Nikoloski, 2020). Since the social risks scale with costs in the PSILCA method, price fluctuations might influence the S-LCA results while the supply chain, and the social risks associated with it, in practice might remain the same. To explore the effects of price fluctuations in a product on the S-LCA results, a sensitivity analysis was conducted with a 50% price increase for vanadium. In this scenario, vanadium takes up a share of 6.91% instead of 4.65% (base case) of the total battery costs (Supporting Information S1, section 4, Table S20).

FIGURE 3 Social risk indicators for lithium ion battery (left) and vanadium redox-flow battery (right), measured in medium-risk work hours. See Supporting Information, section 6 for a numerical overview of the results.

3 | RESULTS

3.1 | Results LIB

3.1.1 | LIB: Workers

For workers, the indicator associated with the highest risks is "*Fair salary*," followed by "*Association rights*," "*Violations of employment regulations*," and "*Trafficking in persons*" (Figure 3). As expected, social risks related to a battery with NMC cathode are higher than those associated with a battery with LMO cathode, either produced in China or Germany. When looking at the contribution tree (CT) of the battery, this is directly linked to the cobalt mining sector in Congo, accounting for more than 30% of the social risks for the "*Fair salary*" indicator (Supporting Information S1, section 7.7), and similar risks for other indicators in the workers stakeholder group.

This also leads to a relatively high risk for child labor for a LIB with NMC cathode, which is a minor risk for a LIB with LMO cathode produced in China and no risk at all for one manufactured in Germany. Moreover, a LIB produced in China generally entails higher social risks than one manufactured in Germany. The only indicator associated with a higher risk in Germany is "*Trade union density*," which reflects the percentage of workers united in a trade union. Apparently "*Fair salary*" is also associated with risks in Germany. When looking at the PSILCA manual, the required living wage in Germany exceeds the minimum wage, due to higher living costs in the country.

The Sankey diagrams (Figure 4) reveal that, for a LIB life cycle in China as well as in Germany, the cathode and the anode are the battery components associated with the highest social risks due to the raw materials and chemicals used, which are derived from sectors causing high risks for workers. Moreover, the figure indicates the use phase of the battery also entails considerable risks due to the electricity that is used during operation. For the life cycle in Germany, the electricity used in the battery operation and battery maintenance takes up a larger share in the total risks for the workers. This is due to the rest of the battery production process in Germany being associated with less risks compared to the same process in

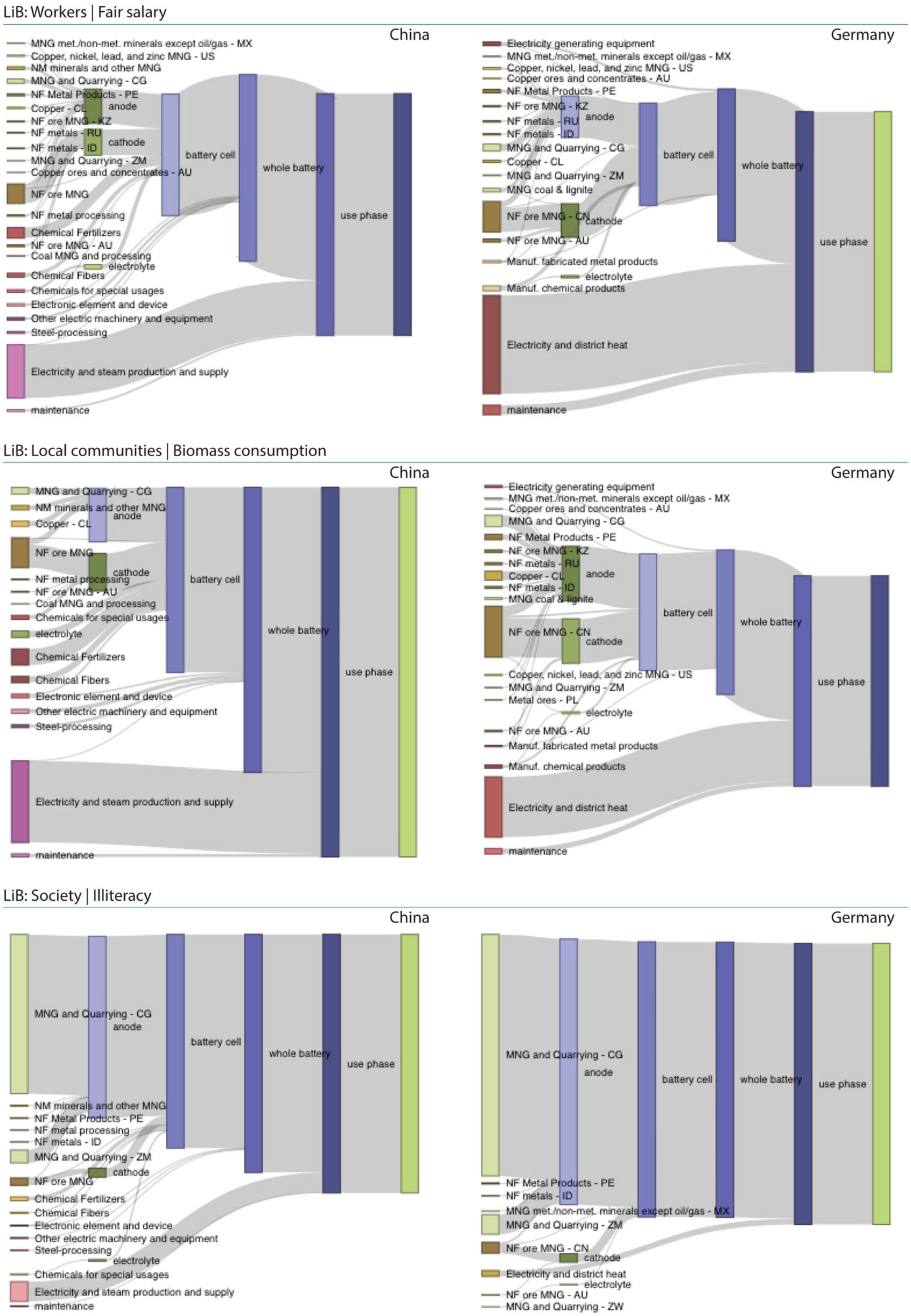

FIGURE 4 Impact contributions for selected social risk indicators: Lithium-ion battery. See the Supporting Information, section 6, for a numerical overview of the results.

China. In the figure, these values are given for the "*Fair salary*" indicator for the worker stakeholder category, but the contributions are similar for other indicators in this category.

3.1.2 | LIB: Local community

For the local community stakeholder group, the indicators that entail the highest risks are "*Extraction of biomass*," "*Pollution level of the country*," and "*Extraction of minerals*" (Figure 3). Again, the risks are highest for an LIB with NMC cathode, followed by an LIB with LMO cathode produced in China, and finally the battery produced in Germany. When considering the Sankey diagrams (Figure 4), the social risks are mainly associated with the raw material extraction stages of the supply chain, which explains the indicators that score highest.

The battery components mainly contributing to the risk are the anode and the cathode again, with the raw material extraction stages having the largest share in the risks. The sectors related to chemicals do not contribute any risks to the local community in the German life cycle, while they do influence the risks in the Chinese supply chain. This indicates these sectors are associated with higher social risks for the local community in China compared to Germany. The use phase also entails considerable risks, especially due to the electricity used. Again the influence of the use phase is larger in the German process due to the lower risks associated with the other stages of the life cycle.

3.1.3 | LIB: Society

Society is the stakeholder with the lowest risks. Especially for the LIB with LMO cathode, either produced in China or in Germany, the risks are very low or even non-existent. For the LIB with NMC cathode, there are some risks regarding illiteracy and health expenditure, and minor risks for a lower life expectancy at birth. The total illiteracy rate for the LIB with NMC cathode is almost fully caused by the mining and quarrying sector in Congo (Figure 4). This also explains why the other LIB types do not score similarly for this indicator. Remarkably, the indicator "contribution of the sector to economic development" scores rather low. This positive indicator measures to what extent the economy benefits from the supply chain. A large contribution to the economy may eventually lead to improved societal conditions, but this does not appear to be the case for the LIB life cycle.

3.2 | Results VRFB

3.2.1 | VRFB: Workers

For the workers stakeholder group, "*Right of association*,", "*Fair salary*," "*Violations of employment laws and regulations*," and "*Trafficking in persons*" are the indicators with the highest risks attached to them, for all three different VRFB supply chains (Figure 3). The LIB also scores highest on these indicators. As expected, the VRFB with the more expensive vanadium entails the highest social risks, closely followed by the VRFB benchmark. The VRFB manufactured in Germany entails lower social risks, except for "*Trade union density*." Battery manufacturing in China seems to be associated with some risk for child labor, while this is a very minor risk when assembly takes place in Germany.

When considering the Sankey diagrams (Figure 5) it is revealed that, for the benchmark supply chain in China, the membrane, gaskets, and electrolyte are the battery components contributing most to the social risks, mainly related to the raw materials and chemicals used in these components. In the German life cycle, the electrolyte, membrane, gaskets, and cables are responsible for the highest risk contributions, also due to the raw materials and chemicals they contain. The use phase entails risks related to maintenance and electricity use. Especially in the German supply chain this takes up a considerable share of the total risks. Since the rest of the life cycle entails lower risks in Germany, maintenance takes up a larger share.

3.2.2 | VRFB: Local community

The social risks for the local community are mainly caused by "*Extraction of biomass*," "*Pollution*," and "*Extraction of minerals*," for all three different VRFB supply chains (Figure 3). This is the case for both the VRFB and the LIB. Again, the VRFB with increased vanadium price scores highest, a little higher than the VRFB with a supply chain in China. The supply chain with the lowest risk scores for these indicators is the one located in Germany. When looking at the Sankeys (Figure 5), most risks are connected to the raw material extraction and chemical material production stages, which explains the high scores for the indicators for biomass and minerals extraction and pollution.

The risks for the local community generally follow from the membrane, the electrolyte, and the gaskets, respectively (see Figure 5 and Supporting Information S1, sections 7.11, 7.14). Again, most risks are related to the sectors related to chemicals (the Chinese sectors "*chemicals for special*

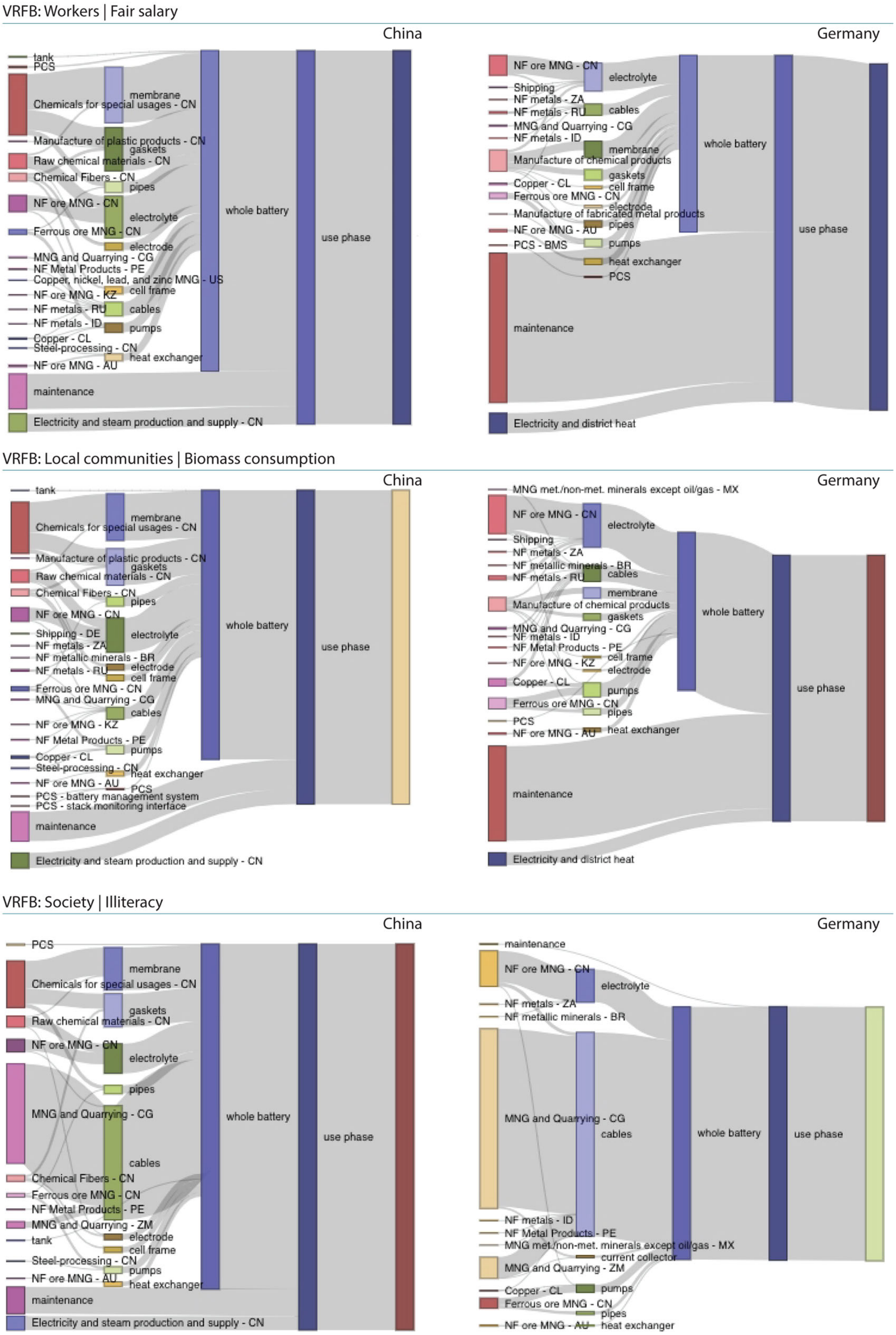

FIGURE 5 Impact contributions for selected social risk indicators: Vanadium redox-flow battery. See the Supporting Information, section 6 for a numerical overview of the results.

usages," "*raw chemical materials*," and "*chemical fibers*"). In the supply chain with the more expensive vanadium (Supporting Information S1, section 7.17), the raw material extraction sectors are related to more risks due to the increased vanadium costs. In the German supply chain, the chemicals sectors cause less risks; in this product system, the main risks are caused by the raw material extraction stages. Since the chemicals in this supply chain are manufactured in Germany, they cause fewer risks due to improved conditions for the local community compared to China. In the use phase, maintenance also contributes considerably to the social risks, especially in the German life cycle. Again, this can be explained since the risks for the German process are lower which results in a larger share of risks contributed to maintenance.

3.2.3 | VRFB: Society

The risks are, like with the LIB, a lot lower for society than for the workers and the local community. Although it has relatively low risk compared to the indicators for the other stakeholder groups, health expenditure is the society-related indicator that entails the highest risk for the VRFB. Similar to the LIB, the contribution of the sector to economic development is not very large.

The Sankeys (Figure 5) show the risks are mainly caused by the cables for both Germany and China, followed by the membrane, gaskets, and electrolyte for China. In the benchmark supply chain, the chemicals and non-ferrous ore mining sectors account for the largest part of the risks. In the German supply chain, the raw material extraction stages are even more influential in the risks, since the rest of the processes are associated with lower risks. This explains the large impacts of the cables which can be almost fully appointed to the mining sector in Congo, responsible for a part of the copper the cables contain.

4 | DISCUSSION

4.1 | Implications for the BESS

4.1.1 | Risks related to raw materials and chemicals

For both the LIB and the VRFB, most social risks are related to the raw material extraction stage in the life cycle, and the risks are lower in Germany compared to China. This corresponds with the findings of Thies et al. (2019) for the LIB. There are several ways to reduce the social risks associated with this stage of the supply chain. These same principles can be applied to the sectors related to chemicals, which, according to our analysis, also entail considerable social risks.

First, social conditions should be improved in these sectors. BESS manufacturers could influence this by vertical integration of suppliers or conducting due diligence of their supply chain. Currently, social problems such as bad working conditions, pollution, and conflicts are caused by these sectors for workers, the local community, and society. Examples can, among others, be found in China (Yang & Ho, 2019; Yang et al., 2017) or in Chile (Camacho, 2012; Liu & Agusdinata, 2020), countries associated with the supply chain of the batteries discussed in this paper. Our results confirm these problems in the supply chain of LIB and VRFB, in which indicators like fair salary, trafficking in persons, right of association, and pollution level of the country are clear hotspots.

Second, some materials might be avoided or substituted to avoid social risks. The LIB used as a benchmark in this paper was a LIB with LMO cathode (Sadhukhan & Christensen, 2021). From our analysis it becomes clear that a LIB with NMC cathode entails considerably higher social risks than one with a LMO cathode, mainly due to cobalt mining in Congo. As also proposed by other authors (Sharma & Manthiram, 2020), we therefore advise the use of LIB with LMO cathode instead of NMC cathode. This stance is supported when considering the environmental impacts, which are lower for LMO cathode compared to NMC cathode (Yin et al., 2019).

Third, the lifetime or efficiency of these batteries could be improved to reduce social risks related to the battery life cycle. If a longer life cycle is ensured or higher efficiency is achieved, the relative contribution of the different life cycle stages decreases because the effects are spread out over more kWh of energy delivery. Extending the life cycle seems to have the most potential for the LIB, which currently operates for up to 2000 cycles (Diouf & Pode, 2015). The VRFB, on the other hand, has a longer cycle life but lower energy efficiency (75%) and lower depth of discharge (DoD) (60%) (Moore, 2013; Skyllas-Kazacos et al., 2016; Weber et al., 2018). These values are significantly higher for the LIB. If these can be improved, energy outputs in kWh per kg battery increase, and thus the relative social risks per kWh decline. Preferably this would be achieved without much additional maintenance, to limit the social risks related to maintenance of the batteries.

4.1.2 | End-of-life scenarios

A fourth way of reducing the social risks related are reuse and recycling of materials, however this may also entail social risks itself. For end-of-life (EOL), the VRFB has a large advantage, since it can theoretically be used endlessly by just renewing the electrolyte and by doing maintenance and replacements of components (Dieterle et al., 2022; Skyllas-Kazacos et al., 2016; Weber et al., 2018). For the VRFB the social risks related to maintenance, as indicated in our results, might thus be outweighed by the lack of risks related to its EOL process. For LIB, this is not the case and considering the social risks of EOL is important. Dealing with EOL LIBs, which may entail landfilling, incineration, full or partial recycling, informal disposal and reprocessing, always entails social risks. The disposed batteries may burst into flames or release gases and droplets of solvent composed of toxic and explosive gases (Mrozik et al., 2021). In this section, the social implications of three different EOL pathways will be explored.

Reuse

In contrast to EV batteries, reuse of larger-scale LIB ESS is not likely due to degradation of the batteries. Efficiency degradation in the product might make reuse unfavorable compared to a new BESS for the same application; using a new one might entail less environmental impacts (Richa et al., 2017). The social risks, however, would most likely decrease when batteries are reused, since the use phase of the battery is not associated with large risks compared to the raw material extraction and manufacturing phases. Yet, it is debatable whether reuse of BESS would be a realistic option, since there are not many other applications thinkable for these systems.

Recycling

By recycling batteries, a great degree of eco-toxicity impact can be avoided because it prevents leakage from landfills (Richa et al., 2017). Compared to small-scale batteries, it is more likely larger high-power batteries are recycled or recovered due to the amounts of valuable materials they contain (Mrozik et al., 2021). Approximately 60% of lithium could be supplied by recovered lithium in the future (Qiao et al., 2021), and in the most optimistic scenario around 65% of copper demand can be filled with recycled scrap (Ciacci et al., 2020). When assuming a decrease of 60% in primary lithium inputs and 65% less primary copper inputs, "*Fair salary*" and "*Biomass consumption*" risks for the LIB (benchmark, China) are reduced by 5% (see Supporting Information S1, section 8).

However, recycling processes also generate NO_x and Cl_2 and acid fumes due do the presence of HNO_3 (Garole et al., 2020). This entails environmental but also social risks since it causes pollution and potential health impacts. Moreover, the crushing of LIBs during the processing can also lead to fires or explosions with toxic smoke and gas emissions, resulting in social risks for the workers involved in the recycling process but also for people living in proximity of recycling facilities. Recycling can also require large amounts of energy, leading to GHG emissions and toxic gases or hazardous slag that may need to be landfilled (Mrozik et al., 2021). Considering the rather minor decrease in risk scores and the social risks related to recycling processes, it is thus questionable whether recycling actually entails social benefits.

Landfill

Disposal in landfills is currently the most common way to process LIB waste (Khawaja et al., 2019; Mrozik et al., 2021; Richa et al., 2017), and reportedly as high as 70% of LIB waste may end up in landfills (Richa et al., 2017) due to a lack of effective battery waste collection schemes in many countries (Khawaja et al., 2019). This entails considerable risks, ranging from the loss of valuable materials, the potential leaching of metals and toxins into the soil, groundwater, and surface water (Richa et al., 2017; Mrozik et al., 2021), to landfill fires which may release toxic gases and produce smoke with detrimental effects on the environment and human health. Often E-waste, under which batteries are categorized, is exported from rich countries to developing countries to be processed or disposed there, resulting in burden shifting (Mrozik et al., 2021). In these countries waste management practices are generally lacking, for example, with large informal waste recycling practices resulting in large social impacts (Rodrigues et al., 2020; Umair et al., 2015).

Further research is required to assess the potential social impacts of battery EOL scenarios and to determine whether the benefits of recycling outweigh its potential impacts from a social perspective.

4.2 | Reflections on the methodology

4.2.1 | Country-wide indicators

In the PSILCA database, indicators are often measured with country-wide instead of sector-based data (Maister et al., 2020). This raises the question whether these indicators can actually say that much about the social circumstances in the battery supply chain. For example, working conditions and social risks are often worse in raw material extraction compared to other sectors in a country (Camacho, 2012; Liu & Agusdinata, 2020; Yang & Ho, 2019; Yang et al., 2017). Simultaneously, the risks in practice may also be less problematic than S-LCA results indicate. Even if indicators are measured sector based, differences in locations and companies are not considered. Social risks may differ from company to company or mine to mine depending on company policy or management. The implementation of corporate social responsibility (CSR) policies and health and safety management systems such as ISO45001 differs considerably from company to company, and this might influence the social risks related to a particular mining site (Frederiksen, 2018; ICMM, 2021; Pons et al., 2021). Some companies, for example, Fairphone, try to stimulate responsible sourcing of the materials they use in their products by establishing partnerships (Fairphone, n.d.). S-LCA results should therefore be interpreted carefully, and rushed generalizations should be prevented.

4.2.2 | Cost sensitivity

As touched upon before, the PSILCA database directly scales the social risks to the costs of a product. This entails some challenges in using the database. Different product life cycles can only be compared when they are based on similar cost data. The ecoinvent cost data (Wernet et al., 2016), which are used as a basis of this S-LCA, comes from different sources with multiple underlying assumptions. This increases uncertainty of the results. Since the reported levelized storage costs in a recent study by Xu et al. (2022) differ considerably from the costs based on the method used in this paper (see Supporting Information S1, section 3), we focus on the relative risks between battery components within each battery rather than comparing batteries. The cost sensitivity also leads to problems when assessing emerging technologies, which have yet to go through a learning curve that will most likely lead to lower costs in the future. This is the case for LIB but even more for VRFB for which a reduction of installed cost by two thirds by 2030 has been projected (IRENA, 2017). The cost sensitivity of the methodology also explains the large contribution of the battery maintenance in the risk results, since maintenance, especially for the VRFB, is a considerable part of the total costs. However, in practice it is not very likely maintenance is related to large social risks (Whitehead et al., 2017). Since S-LCA is aimed as a tool to inform decision-making and create more socially friendly products (UNEP/SETAC, 2020), the inappropriateness to assess the risks related to emerging technologies is a major shortcoming of conducting an S-LCA through the PSILCA database.

Frequent price fluctuations of certain components or materials within a life cycle are also problematic. Our analysis shows a price increase of vanadium of 50% results in higher risks for a similar supply chain, even though the total share of vanadium in the battery costs is only around 7%. Scaling the social risks based on costs leads to fundamental problems with the methodology. Social conditions do not necessarily deteriorate in practice when prices increase. Hypothetically, a product may be produced under very bad working conditions, maybe even involving child labor. These child laborers are paid badly and a safe working environment is not facilitated, which will likely decrease the costs of the product. The social risks resulting from the assessment of this supply chain in PSILCA are lower compared to a product life cycle in which a lot of attention is given to positive social conditions which is in turn reflected in higher costs and thus higher risk results in PSILCA. Especially since the attention for S-LCA in policies is increasing (European Commission, 2020), and the S-LCA guidelines recommends the use of S-LCA databases (UNEP/SETAC, 2020), we believe it is important to emphasize that the social risks resulting from an S-LCA with the help of PSILCA do not necessarily reflect impacts in reality, and additional research is required to confirm these results. The results could still provide valuable information on the potential social risk hotspots, although practitioners should be aware of the shortcomings.

4.2.3 | Temporal variability and future trends

Another factor to consider while interpreting S-LCA results is temporal variability and future trends. Although our results indicate risks associated with a battery supply chain in China, this does not necessarily have to be the same in a few years from now. According to World Bank projections, China's technological progress will bring rapid change to its industrial structure, with raising standards for quality, safety, and the environment (World Bank, 2013). This will result in China's implementation of internationally recognized standards such as ISO45001 and ISO14001. Thus, the social risks related to a product life cycle may soon be different due to developments within the countries associated with it. Generalizing S-LCA results from the past to the present or the future should thus be done carefully.

4.2.4 | Limited attention for positive socio-economic effects

Although there are some positive indicators, such as the contribution to economic development, the results of the S-LCA in PSILCA mainly indicate the negative social risks related to a product's life cycle. Some authors argue that life cycle sustainability assessment, which encompasses S-LCA, should take a broad focus on human well-being (Schaubroeck & Rugani, 2017). Assessing the contributions of the mining sector to society beyond the added economic value remains a challenge in sustainability assessment (Mancini & Sala, 2018). This also applies to assessing the societal contributions of products like batteries. Currently these benefits are not accounted for in an S-LCA conducted through the PSILCA database. Taking the broader advantages of a product into account raises many philosophical and political questions. An extra difficulty arises when the negative impacts along the supply chain take place in countries with a low socio-economic status, while the positive impacts at the use phase benefit a wealthier nation (Sovacool et al., 2020). Some authors have already advocated an increased focus on the positive social effects in S-LCA methodology (Di Cesare et al., 2018; Ekener et al., 2016; Kühnen & Hahn, 2019), and it would be advantageous to also incorporate this into databases like PSILCA.

5 | CONCLUSIONS

Altogether, most social risks related to the life cycle of LIB and VRFB are associated with the raw material extraction stage. Sectors related to chemicals also entail considerable social risks. Besides, maintenance also takes up a large share in the total risks, especially in the German supply chains due to the risks from the other processes being lower there. Workers are the stakeholder group affected most, followed by the local community. Society was affected to a considerably smaller extent. These results apply to supply chains located in both examined countries, China and Germany. Risks were substantially lower for a similar supply chain in Germany for almost all examined indicators. With a different LIB composition, with NMC cathode instead of LMO cathode, the social risks were drastically higher due to the use of cobalt. For a VRFB with an increased vanadium price, the social risks were higher than those of the VRFB supply chain with the regular vanadium price, illustrating the cost sensitivity of the methodology.

Here we show that S-LCA results can assist in making justified and explainable decisions, and thus prevent unwanted and sometimes unknown burden shifting from environmental to social sustainability. It is also demonstrated that generalizing the results should not be done or should be done very carefully due to methodological constraints. First, indicators are often measured through country-wide data, making it difficult to draw sector-specific conclusions. Second, the risk results are directly tied to the costs of a product. When comparing different products, cost data must be comparable. This cost sensitivity may cause problems when price fluctuations occur. Moreover, this makes the method inappropriate for assessing emerging technologies that are still going through a technology learning curve. Third, detailed data on a product's supply chain is required, such as the location of supply chain processes, which may be difficult to obtain. Altogether, an S-LCA conducted with the PSILCA database might provide interesting insights into the social risk hotspots along the life cycle of products, but one should be aware that the results only indicate potential social impacts and ideally would have to be confirmed by additional research.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supporting information of this article.

ORCID

Maarten Koese https://orcid.org/0000-0002-0128-1161
Carlos F. Blanco https://orcid.org/0000-0001-8199-8420
Martina G. Vijver https://orcid.org/0000-0003-2999-1605

REFERENCES

Almanza, A., & Corona, B. (2020). Using social life cycle assessment to analyze the contribution of products to the sustainable development goals: A case study in the textile sector. *International Journal of Life Cycle Assessment*, *25*, 1833–1845. https://doi-org.ezproxy.leidenuniv.nl/10.1007/s11367-020-01789-7

Amnesty International. (2016). *This is what we die for: Human rights abuses in the Democratic Republic of the Congo power the global trade in cobalt.* Amnesty International.

Bouillass, G., Blanc, I., & Perez-Lopez, P. (2021). Step-by-step social life cycle assessment framework: A participatory approach for the identification and prioritization of impact subcategories applied to mobility scenarios. *The International Journal of Life Cycle assessment*, *26*(12), 2408–2435. https://doi.org/10.1007/s11367-021-01988-w

Bueno, G., De Blas, M., Perez-Iribarren, E., Zuazo, I., Torre-Pascual, E., Erauskin, A., Extano, I., Tamayo, U., Garcia, N., Akizu-Gardoki, O., Leon, I., Marieta, C., Zulueta, G., & Barrio, I. (2021). The environmental and social footprint of the university of the Basque Country UPV/EHU. *Journal of Cleaner Production*, *315*, 128019. https://doi.org/10.1016/j.jclepro.2021.128019

Camacho, F. (2012). Competing rationalities in water conflict: Mining and the indigenous community in Chiu Chiu, El Loa Province, northern Chile. *Singapore Journal of Tropical Geography*, *33*(1), 93–107. https://doi.org/10.1111/j.1467-9493.2012.00451.x

Ciacci, L., Fishman, T., Elshkaki, A., Graedel, T., Vassura, I., & Passarini, F. (2020). Exploring future copper demand, recycling and associated greenhouse gas emissions in the EU-28. *Global Environmental Change*, *63*, 1–10. https://doi.org/10.1016/j.gloenvcha.2020.102093

Ciotola, A., Fuss, M., Colombo, S., & Poganietz, W. (2021). The potential supply risk of vanadium for the renewable energy transition in Germany. *Journal of Energy Storage*, *133*, 102094. https://doi.org/10.1016/j.est.2020.102094

Ciroth, A., & Eisfeldt, F. (2016). *PSILCA—A product social impact life cycle assessment database.* GreenDelta.

Denholm, P., & Hand, M. (2011). Grid flexibility and storage required to achieve very high penetration of variable renewable electricity. *Energy Policy*, *39*(3), 1817–1830. https://doi.org/10.1016/j.enpol.2011.01.019

Dai, Q., Kelly, J., Dunn, J., & Benavides, P. (2018). *Update of bill-of-materials and cathode materials production for lithium-ion batteries in the GREET model*. https://greet.es.anl.gov/publication-update_bom_cm

Di Cesare, S., Silveri, F., Sala, S., & Petti, L. (2018). Positive impacts in social life cycle assessment: State of the art and the way forward. *The International Journal of Life Cycle Assessment*, *23*, 406–421. https://doi.org/10.1007/s11367-016-1169-7

Dieterle, M., Fischer, P., Pons, M., Blume, N., Minke, C., & Bischi, A. (2022). Life cycle assessment (LCA) for flow batteries: A review of methodological decisions. *Sustainable Energy Technologies and Assessments*, *53*, 102457. https://doi.org/10.1016/j.seta.2022.102457

Di Noi, C., Ciroth, A., Mancini, L., Eynard, U., Pennington, D., & Blengini, G. (2020). Can S-LCA methodology support responsible sourcing of raw materials in EU policy context? *The International Journal of Life Cycle Assessment*, *25*, 332–349. https://doi.org/10.1007/s11367-019-01678-8

Diouf, B., & Pode, R. (2015). Potential of lithium-ion batteries in renewable energy. *Renewable Energy*, *76*, 375–380. https://doi.org/10.1016/j.renene.2014.11.058

Dunn, B., Kamath, H., & Tarascon, J. (2011). Electrical energy storage for the grid: A battery of choices. *Science*, *334*(6058), 928–935. https://doi.org/10.1126/science.1212741

Ekener, E., Hansson, J., & Gustavsson, M. (2016). Addressing positive impacts in social LCA—Discussing current and new approaches exemplified by the case of vehicle fuels. *International Journal of Life Cycle Assessment*, *23*, 556–568. https://doi.org/10.1007/s11367-016-1058-0

Erauskin-Tolosa, A., Bueno, G., Extano, I., Tamayo, U., Garcia, M., De Blas, M., Perez-Irribarren, E., Zuazo, I., Torre-Pascual, E., & Akizu-Gardoki, O. (2021). Social organisational LCA for the academic activity of the University of the Basque Country UPV/EHU. *International Journal of Life Cycle Assessment*, *26*(8), 1648–1669. https://doi.org/10.1007/s11367-021-01940-y

European Commission. (2019). *The European Green Deal*. European Commission. https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1588580774040&uri=CELEX:52019DC0640

European Commission. (2020). *Proposal for a regulation concerning batteries and waste batteries*. European Commission. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020PC0798

European Commission. (2022). *Proposal for a regulation establishing a framework of measures for strengthening Europe's semiconductor ecosystem (Chips Act)*. European Commission. https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=COM:2022:45:FIN

Fairphone. (n.d.). *Responsible sourcing from conflict areas*. Fairphone. https://www.fairphone.com/en/project/responsible-sourcing/

Figgener, J., Stenzel, P., Kairies, K., Linssen, J., Haberschusz, D., Wessels, O., Angenendt, G., Robinius, M., Stolten, D., & Sauer, D. (2020). The development of stationary battery storage systems in Germany – A market review. *Journal of Energy Storage*, *29*, 101153. https://doi.org/10.1016/j.est.2019.101153

Frederiksen, T. (2018). Corporate social responsibility, risk and development in the mining industry. *Resources Policy*, *59*, 495–505. https://doi.org/10.1016/j.resourpol.2018.09.004

Garole, D. J., Hossain, R., Garole, V. J., Sahajwalla, V., Nerkar, J., & Dubal, D. P. (2020). Recycle, recover and repurpose strategy of spent Li-ion batteries and catalysts: Current status and future opportunities. *ChemSusChem*, *13*(12), 3079–3100. https://doi.org/10.1002/cssc.201903213

Gilligan, R., & Nikoloski, A. (2020). The extraction of vanadium from titanomagnetites and other sources. *Minerals Engineering*, *146*, 1–18. https://doi.org/10.1016/j.mineng.2019.106106

Gür, T. (2018). Review of electrical energy storage technologies, materials and systems: Challenges and prospects for large-scale grid storage. *Energy & Environmental Science*, *11*, 2696–2767. https://doi.org/10.1039/c8ee01419a

Hannouf, M., & Assefa, G. (2018). Subcategory assessment method for social life cycle assessment: A case study of high-density polyethylene production in Alberta, Canada. *The International Journal on Life Cycle Assessment*, *23*, 116–132. https://doi.org.ezproxy.leidenuniv.nl/10.1007/s11367-017-1303-1

ICMM, International Council on Mining and Metals. (2021). Safety performance: Benchmarking progress of ICMM company members in 2020. *International Council on Mining and Metals*, https://www.icmm.com/website/publications/pdfs/health-and-safety/2021/benchmarking-safety-data-2020.pdf

IEA, International Energy Agency. (2020). Innovation in batteries and electricity storage. *International Energy Agency*, https://www.iea.org/reports/innovation-in-batteries-and-electricity-storage

IEA, International Energy Agency. (2021a). World energy outlook 2021. *International Energy Agency*, https://www.iea.org/reports/world-energy-outlook-2021/a-new-energy-economy-is-emerging

IEA, International Energy Agency. (2021b). The role of critical minerals in clean energy transitions. *International Energy Agency*, https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions

IRENA. (2017). Electricity storage and renewables: Costs and markets to 2030. *International Renewable Energy Agency*, https://www.irena.org/publications/2017/Oct/Electricity-storage-and-renewables-costs-and-markets

Jowitt, S., Mudd, G., & Thompson, J. (2020). Future availability of non-renewable metal resources and the influence of environmental, social, and governance conflicts on metal production. *Communications, Earth & Environment*, *1*(13), 1–8. https://doi.org/10.1038/s43247-020-0011-0

Jung, R., Metzger, M., Maglia, F., Stinner, C., & Gasteiger, H. (2017). Oxygen release and its effect on the cycling stability of $LiNi_xMn_yCo_zO_2$ (NMC) cathode materials for Li-ion batteries. *Journal of the Electrochemical Society*, *164*(7), 1361–1377. https://doi.org/10.1149/2.0021707jes

Khawaja, M., Alkhalidi, M., & Mansour, S. (2019). Environmental impacts of energy storage waste and regional legislation to curtail their effects - Highlighting the status in Jordan. *Journal of Energy Storage*, *26*, 100919. https://doi.org/10.1016/j.est.2019.100919

Kühnen, M., & Hahn, R. (2019). From SLCA to positive sustainability performance measurement: A two-tier Delphi study. *Journal of Industrial Ecology*, *23*(3), 615–634. https://doi.org/10.1111/jiec.12762

Lenzen, M., Kanemoto, K., Moran, D., & Geschke, A. (2012). Mapping the structure of the world economy. *Environmental Science & Technology*, *46*(15), 8374–8381. http://doi.org/10.1021/es300171x

Lenzen, M., Moran, D., Kanemoto, K., & Geschke, A. (2013). Building Eora: A global multi-region input–output database at high country and sector resolution. *Economic Systems Research*, *25*(1), 20–49. https://doi.org/10.1080/09535314.2013.769938

Liu, W., & Agusdinata, D. (2020). Interdependencies of lithium mining and communities sustainability in Salar de Atacama, Chile. *Journal of Cleaner Production*, *260*, 1–13. https://doi.org/10.1016/j.jclepro.2020.120838

Maister, K., Di Noi, C., Ciroth, A., & Srocka, M. (2020). *PSILCA v.3. – Database documentation*. GreenDelta.

Mancini, L., & Sala, S. (2018). Social impact assessment in the mining sector: Review and comparison of indicators frameworks. *Resources Policy*, *57*, 98–111. https://doi.org/10.1016/j.resourpol.2018.02.002

Martin, M., & Herlaar, S. (2021). Environmental and social performance of valorizing waste wool for sweater production. *Sustainable Production and Consumption*, *25*, 425–438. https://doi.org/10.1016/j.spc.2020.11.023

Martin-Gamboa, M., Dias, A., Arroja, L., & Irribarren, D. (2020). A protocol for the definition of supply chains in product social life cycle assessment: Application to bioelectricity. *Sustainable Energy Fuels*, *4*, 5533–5542. https://doi.org/10.1039/d0se00919a

Mohamad, F., Teh, J., Lai, C., & Chen, L. (2018). Development of energy storage systems for power network reliability: A review. *Energies*, *11*(9), 1–19. https://doi.org/10.3390/en11092278

Moore, M. (2013). *A base case design and capital cost analysis of an all vanadium redox-flow battery*. University of Tennessee.

Mrozik, W., Rajaeifar, M., Heidrich, O., & Christensen, P. (2021). Environmental impacts, pollution sources, and pathways of spent lithium-ion batteries. *Energy & Environmental Science*, *14*(12), 6099–6121. https://doi.org/10.1039/D1EE00691F

Muller, S., Beylot, A., Sydd, O., Doyle, K., Bodin, J., & Villeneuve, J. (2021). Applying social life cycle assessment in the early stages of a project development — An example from the mining sector. *International Journal of Life Cycle Assessment*, *26*, 2436–2456. https://doi.org/10.1007/s11367-021-01995-x

Pindyck, R. (2004). Volatility and commodity price dynamics. *Journal of Future Markets*, *24*(11), 1029–1047. https://doi.org/10.1002/fut.20120

Pons, A., Vintro, C., Rius, J., & Vilaplana, J. (2021). Impact of corporate social responsibility in mining industries. *Resources Policy*, *72*, 1–13. https://doi.org/10.1016/j.resourpol.2021.102117

Qiao, D., Wang, G., Gao, T., Wen, B., & Dai, T. (2021). Potential impact of the end-of-life batteries recycling of electric vehicles on lithium demand in China: 2010–2050. *Science of the Total Environment*, *764*, 142835. https://doi.org/10.1016/j.scitotenv.2020.142835

Richa, K., Babbitt, C., & Gaustad, G. (2017). Eco-Efficiency analysis of a lithium-ion battery waste hierarchy inspired by circular economy. *Journal of Industrial Ecology*, *21*(3), 715–730. https://doi.org/10.1111/jiec.12607

Rodrigues, L., Angelo, A., & Marujo, L. (2020). Conceptual framework to social life cycle assessment of e-waste management: A case study in the city of Rio de Janeiro. In Singh, P., Singh, R., Srivastava, V. (Eds), *Contemporary environmental issues and challenges in era of climate change*. Springer.

Sadhukhan, J., & Christensen, M. (2021). An in-depth life cycle assessment (LCA) of lithium-ion battery for climate impact mitigation strategies. *Energies*, *14*(17), 5555. https://doi.org/10.3390/en14175555

Schaubroeck, T., & Rugani, B. (2017). A revision of what life cycle sustainability assessment should entail: Towards modeling the net impact on human well-being. *Journal of Industrial Ecology*, *21*(6), 1464–1477. https://doi.org/10.1111/jiec.12653

Serreli, M., Petti, L., Raggi, A., Simboli, A., & Iuliano, G. (2021). Social life cycle assessment of an innovative industrial wastewater treatment plant. *The International Journal of Life Cycle Assessment*, *26*(9), 1878–1899. https://doi.org/10.1007/s11367-021-01942-w

Sharma, S., & Manthiram, A. (2020). Towards more environmentally and socially responsible batteries. *Energy & Environmental Science*, *13*, 4087–4097. https://doi.org/10.1039/D0EE02511A

Skyllas-Kazacos, M., Cao, L., Kazacos, M., Kausar, N., & Mousa, A. (2016). Vanadium electrolyte studies for the vanadium redox battery – A review. *ChemSusChem*, *9*(13), 1521–1543. https://doi.org/10.1002/cssc.201600102

Sovacool, B., Hook, A., Martiskainen, M., Brock, A., & Turnheim, B. (2020). The decarbonisation divide: Contextualizing landscapes of low-carbon exploitation and toxicity in Africa. *Global Environmental Change*, *60*, 1–19. https://doi.org.ezproxy.leidenuniv.nl/10.1016/j.gloenvcha.2019.102028

Sprecher, B., & Kleijn, R. (2021). Tackling material constraints on the exponential growth of the energy transition. *OneEarth*, *4*(3), 335–338. https://doi.org/10.1016/j.oneear.2021.02.020

Sureau, S., Mazijn, B., Garrido, S. R., & Achten, W. (2018). Social life-cycle assessment frameworks: A review of criteria and indicators proposed to assess social and socioeconomic impacts. *International Journal of Life Cycle Assessment*, *23*, 904–920. http://doi.org/10.1007/s11367-017-1336-5

Thies, C., Kieckhäfer, K., Spengler, T., & Sodhi, M. (2019). Assessment of social sustainability hotspots in the supply chain of lithium-ion batteries. *Procedia CIRP*, *80*, 292–297. https://doi.org/10.1016/j.procir.2018.12.009

Umair, S., Bjorklund, A., & Petersen, E. E. (2015). Social impact assessment of informal recycling of electronic ICT waste in Pakistan using UNEP SETAC guidelines. *Resources, Conservation and Recycling*, *95*, 46–57. https://doi.org/10.1016/j.resconrec.2014.11.008

USGS (United States Geological Survey). (2021). *National Minerals Information Center: Vanadium statistics and information*. US Department of the Interior. https://www.usgs.gov/centers/national-minerals-information-center/vanadium-statistics-and-information

UN General Assembly. (2015). *Transforming our world: The 2030 agenda for sustainable development*. United Nations.

UNEP/SETAC. (2020). *Guidelines for social life cycle assessment of products and organizations 2020*. United Nations Environment Programme.

Viswanathan, V., Crawford, A., Stephenson, D., Kim, S., Wang, W., Li, B., Coffey, G., Thomsen, E., Graff, G., Balducci, P., Kintner-Meyer, M., & Sprenkle, V. (2014). Cost and performance model for redox flow batteries. *Journal of Power Sources*, *247*, 1040–1051. https://doi.org/10.1016/j.jpowsour.2012.12.023

Weber, S., Peters, J., Bauman, M., & Weil, M. (2018). Life cycle assessment of a vanadium redox flow battery. *Environmental Science and Technology*, *52*(18), 10864–10873. https://doi.org/10.1021/acs.est.8b02073

WEF, World Economic Forum. (2019). *Batteries can power sustainable development. Here's how*. https://www.weforum.org/agenda/2019/01/batteries-can-power-sustainable-development-heres-how/

Werker, J., Wulf, C., Zapp, P., Schreiber, A., & Marx, J. (2019a). Social LCA for rare earth NdFeB permanent magnets. *Sustainable Production and Consumption*, *19*, 257–269. https://doi.org/10.1016/j.spc.2019.07.006

Werker, J., Wulf, C., & Zapp, P. (2019b). Working conditions in hydrogen production: A social life cycle assessment. *Journal of Industrial Ecology*, *23*(5), 1051–1062. https://doi.org/10.1111/jiec.12840

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). The ecoinvent database version 3 (part I): overview and methodology. *The International Journal of Life Cycle Assessment*, *21*(9), 1218–1230. http://link.springer.com/10.1007/s11367-016-1087-8

Whitehead, A., Rabbow, T., Trampert, M., & Pokorny, P. (2017). Critical safety features of the vanadium redox flow battery. *Journal of Power Sources*, *351*, 1–7. https://doi.org/10.1016/j.jpowsour.2017.03.075

World Bank, and the Development Research Center of the State Council, P. R. China. (2013). *China 2030: Building a modern, harmonious, and creative society*. World Bank. https://doi.org/10.1596/978-0-8213-9545-5

Xu, Y., Pei, J., Cui, L., Liu, P., & Ma, T. (2022). The levelized cost of storage of electrochemical energy storage technologies in China. *Frontiers in Energy Research*, *10*, 1–16. https://doi.org/10.3389/fenrg.2022.873800

Yang, X., Zhao, H., & Ho, P. (2017). Mining-induced displacement and resettlement in China: A study covering 27 villages in 6 provinces. *Resources Policy*, *53*, 408–418. https://doi.org/10.1016/j.resourpol.2017.07.001

Yang, X., & Ho, P. (2019). Is mining harmful or beneficial? A survey of local community perspectives in China. *The Extractive Industries and Society*, *6*(2), 584–592. https://doi.org/10.1016/j.exis.2019.02.006

Yin, R., Hu, S., & Yang, Y. (2019). Life cycle inventories of the commonly used materials for lithium-ion batteries in China. *Journal of Cleaner Production*, *227*, 960–971. https://doi.org/10.1016/j.jclepro.2019.04.186

Zubi, G., Dufo-Lopez, R., Carvalho, M., & Pasaoglu, G. (2018). The lithium-ion battery: State of the art and future perspectives. *Renewable and Sustainable Energy Reviews*, *89*, 292–308. https://doi.org/10.1016/j.rser.2018.03.002

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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