

Guiding the research on bio-based supercapacitors towards a socially viable value chain development

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ABSTRACT

The transition to sustainable and resource-efficient vehicles is crucial for addressing social conditions and advancing electromobility. Conventional batteries using materials like lithium and cobalt are linked to significant social issues, prompting research into alternatives that avoid those issues. This study evaluates a bio-based supercapacitor under development in the EU project EMPHASIS through a Social Life Cycle Assessment (SLCA), aiming to enhance the social sustainability of electromobility. Supercapacitors offer advantages over batteries, including high power density, rapid charge-discharge cycles, and long operational life. The bio-based supercapacitor utilizes renewable resources for electrodes and bio-electrolytes, avoiding critical raw materials and toxic substances. These innovations promise reduced social impacts compared to conventional energy storage systems. Conducting SLCA during product development faces challenges like uncertain value chains and limited data availability. However, early social sustainability assessments are essential for creating sustainable products. Social risk mapping through expert workshops and secondary data highlights potential impacts across the supercapacitor's hypothetical global value chain. Resource extraction and end-of-life phases are identified as having the highest social implications, particularly for workers. The study underscores the potential of bio-based supercapacitors to significantly improve the social sustainability of electromobility. By leveraging renewable resources and fair manufacturing practices, they can reduce social risks while contributing to broader goals of equity and

sustainable development. These findings provide valuable insights for stakeholders in the automotive and energy sectors, emphasizing the importance of integrating social innovation into next-generation supercapacitor development.

1. INTRODUCTION

Electric vehicles (EV) are a popular alternative to conventional combustion engine vehicles due to their potential for lower greenhouse gas emissions and reduced fossil fuel dependency (Alanazi, 2023). EVs require power sources with high energy density and a long cycle life. Materials used should be cost-effective and available abundantly (Yoo et al., 2014). Rechargeable batteries, such as lithium-ion batteries, are currently the state of the art power source for EVs. However, batteries have several disadvantages, including material ageing, degradation and limited cycling performance (Azega et al., 2024; Schmalstieg et al., 2013; Zhao et al., 2020). Supercapacitors (SC) can be regarded as alternatives to conventional batteries due to their longer life span, ability to be rapidly (dis-) charged, higher cycling performance and minimal material aging or degradation (Azega et al., 2024).

SCs offer advantages in performance, as well as environmental sustainability, compared to batteries but no studies have been performed on their social implications. Achieving social sustainability represents an essential part of sustainable development but has been largely neglected compared to the economic and environmental pillars of sustainability (Hutchins & Sutherland, 2008). Mining activities for lithium or other critical raw materials are associated with social impacts such as “child labour” and “occupational accidents” and are responsible for the severe social impacts of battery and SC value chains and affect multiple stakeholder groups involved in that value chain (Rahimpour et al., 2024). ‘Value chain’ in this context is defined as the complete sequence of activities, processes and actors involved in creating a product or service along its entire life cycle from conception to disposal while systematically considering the associated social and socio-economic impacts at each stage (as depicted in Figure 1) (UNEP, 2020). The SC developed in the EU project EMPHASIS uses bio-based materials like cellulose, lignin and grape molasses produced within the European Union for the current collector and electrode and avoids the use of critical raw materials and mining activities. However, its value chain may still exhibit severe social impacts as studies have shown that upstream processes in agriculture present a high potential for social risks regarding for example poverty, rural development and job

security, especially in countries exporting bio-based materials (Spierling et al., 2018).

Social Life Cycle Assessment (SLCA) is a method used to assess potential social impacts of the bio-based SC along its value chain. SLCA mostly deals with qualitative information such as acceptable working conditions, respect for human and civil rights and equality (Ashby, 2024) and is devoted to the evaluation of potential positive and negative social and socio-economic impacts of a product (Colombo et al., 2024; Dahiya et al., 2020). Noteworthy social hotspots in SLCA on batteries are “child labour”, “forced labour”, “corruption” (Popien et al., 2023; Shi et al., 2023), “labour rights and decent work”, “health and safety” and “human rights” (Thies et al., 2019).

Assessing the sustainability impacts of any product poses complex challenges but in particular for emerging technologies at a low technology readiness level (TRL). Most sustainability assessments are conducted for established systems already in the market, meaning that they are produced on industrial scale and follow a fully determined production process (Blanco et al., 2020). In recent years, environmental assessments, in particular LCAs, focusing on emerging technologies have emerged (prospective or ex-ante LCA) (Cucurachi et al., 2018) and multiple upscaling frameworks have been developed for LCA of emerging technologies (Simon et al., 2014; Tsoy et al., 2020; Weyand et al., 2023). These frameworks recognize that innovations and technologies can most easily be changed and optimized during the development phase of a product (Bergerson et al., 2020; Hetherington et al., 2014). SLCA studies on emerging technologies are challenging because the assessment of social impacts requires data accurately representing the value chain for industrial scale production (Cecere et al., 2024) which is often not available and upscaling a value chain remains difficult. Data collection and data availability represent the largest challenges in any SLCA study but especially when dealing with emerging technologies. Social impacts are hard to predict and are likely to be underestimated during upscaling from laboratory to industrial scale. Some studies have attempted to develop methods to conduct SLCA on different stages of technology development. For example, Haase et al. (Haase et al., 2022) identified specific indicators can already be assessed during the early stages of development of technologies used in the energy sector. Another study showed that sensitivity analysis with alternative scenarios (change production country or energy mix) can increase or decrease social risks due to value chain complexities and therefore proofed the importance of conducting SLCAs already early on in the development phase as it can mitigate future risks and support the development of socially sustainable extraction or production processes (Muller et al., 2021). To combat the lack of product- or site-

specific data, early stage SLCA can use generic or country-specific data to create a preliminary estimation of potential social risks and benefits (Groiß-Fürtner et al., 2023; Mair-Bauernfeind et al., 2020). Generic SLCA is not able to identify the “real-life” social implications but can provide preliminary information on potential social problems, risks, benefits and opportunities (Groiß-Fürtner et al., 2023).

The prioritisation of social factors and impacts is an important first step when conducting a SLCA study as it indicates where the focus should lie (Fürtner et al., 2021), in this study this is done with a stakeholder workshop with stakeholders involved in the development of the SC. The potential social risk of the SC is determined using multiple SLCA approaches. The study shows that bio-based SCs can substantially reduce the social impact of electromobility by using renewable resources, avoiding critical raw materials and ensuring fair manufacturing practices.

2. MATERIALS AND METHODS

SLCA follows the framework for Life Cycle Assessment (LCA) set out in the ISO Norms 14040/44 for Life Cycle Assessment (ISO 14040:2006, n.d.), the ISO Norm 14075 for Social Life Cycle Assessment (ISO 14075:2024, n.d.) and the Guidelines for Social Life Cycle Assessment of Products and Organisations 2020 established by the United Nations Environment Programme (UNEP) (UNEP, 2020). Social impacts are considered to be the consequences on stakeholders in the context of activities along a products value chain, such as resource extraction, manufacturing, distribution, use, recycling and final disposal (UNEP, 2020). SLCA aims to improve a products value chain by providing information on the socio-economic impacts of the product to decision-makers, researchers and developers (Thies et al., 2019). SLCA is complementary to the environmental and economic assessment of a product and thereby provides a more holistic and comprehensive picture of a products sustainability (UNEP, 2020). The assessment is an iterative process that involves multiple steps including completeness, consistency, sensitivity and quality

checks. The sensitivity analysis identifies the significant social impacts, risks, stakeholder groups and life cycle phases (UNEP, 2020).

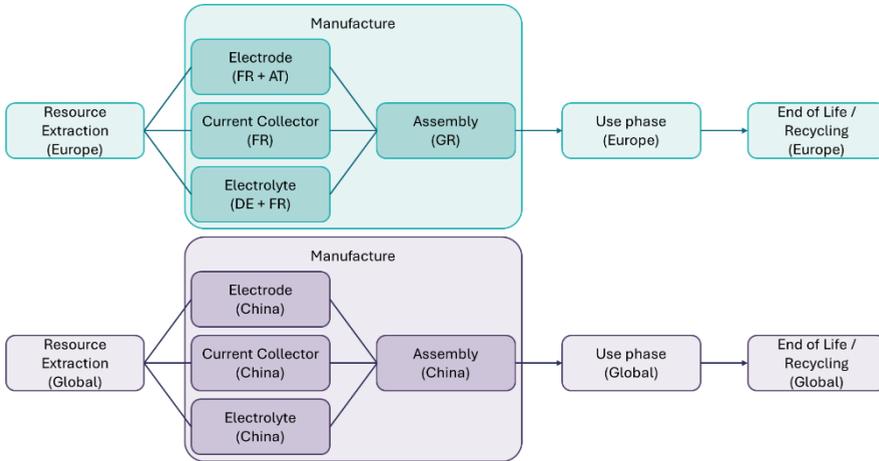


Figure 1: European (top/turquoise) and Global (bottom/purple) value chain of the SC, including country references (source: own figure)

The bio-based SC is currently in development, with production on laboratory scale and a European value chain, with production specifically taking place in Austria, France, Germany and Greece. For an upscaled production a hypothetical global value chain is created with production moving to Asia Pacific, as this region currently produces 38% of the global SCs (Kings Research, 2024). For this assessment China is assumed as the producing country. It can also be assumed that the global value chain has a higher social impact than the European value chain, as developing countries typically exhibit higher social impacts and risks than developed countries (Shi et al., 2023). The European and Global value chains, including the reference regions for resource extraction, manufacturing, use and end of life, are depicted in Figure 1. Transport between the individual production sites is not included in the assessment, as it can be assumed that in an industrial and global value chain production of the electrode, current collector and electrolyte and their assembly are done at the same production site.

A workshop on the prioritisation of social factors in SLCA was held together with the project partners in EMPHASIS in June 2024. The 17 participating project partners were asked to think about any social factors relating to SC production, use and disposal that might positively or negatively affect

workers, society, local communities, value chain actors, consumers or children. All workshop participants can be regarded as being experts in the value chain. As part of the workshop the workshop participants were asked to answer three questions on the platform Mentimeter: 1) What is the area with the highest social impact in SC value chains?, 2) How would you rank the stakeholder groups regarding their vulnerability? and 3) What other stakeholder groups do you perceive as important? In a world café setting, the participants were asked to identify negative and positive social factors that affects each stakeholder group. The stakeholder groups local community and society, as well as consumers and children were grouped together into two larger stakeholder groups.

The potential social risk of the bio-based SC production is assessed using two SLCA approaches: the social risk assessment following the second-level SLCA methodology developed by Groß-Fürtner et al. (Groß-Fürtner et al., 2023) using country or sector specific secondary data and the Social Hotspots Database (SHDB) social risk mapping tool that provides information on the social risk of 132 social indicators for 57 sectors in countries worldwide (SHDB, 2022). For the second-level LCA the stakeholder groups workers, local communities and society across four production countries (Austria, Germany, Greece and France) are included in the assessment. The use of generic data for the assessment allows for an assessment already during the development phase when product specific data is not available and represents the start of an iterative and open-ended assessment process of the bio-based SCs value chain. The social indicators assessed in this study focus largely on the stakeholder group workers. The impact assessment uses the reference point method where the EU-27 averages serve as the reference points for all indicators. The assessment followed a method developed by Zira et al. (Zira et al., 2020), where the social risk potential is considered high with values above 0.5 and values below 0.5 are considered low risk.

The social risk mapping includes the hypothetical Global value chain with production in China. The indicators can be separated into “labour rights and decent work”, “health and safety”, “society”, “governance” and “community”. This web-based tool is used to assess the social risk associated with the automotive and chemical sector for the current European and the hypothetical Global value chain. Within the tool, social risk is categorized into low, medium, high and very high risk; indicators experiencing low risk in all five countries or have missing data for at least one country are omitted from the assessment, which leaves a total of 77 social indicators. Of those 77 indicators 14 are selected to be assessed focusing largely on workers’ health and safety as well as labour regulations.

3. RESULTS

3.1 PRIORITISATION WORKSHOP

The workshop revealed that recycling, production and resource extraction are seen as the three areas with the highest social impact. Consumers were ranked as the most vulnerable stakeholder group, followed by workers. Value chain actors were ranked as the least vulnerable stakeholder group. Policy makers and researchers were named as additional and important stakeholder groups.

For the stakeholder group workers the following social impacts were identified: reduced labour intensity of recycling and disposal (compared to batteries), lower toxicity due to reduced used of heavy metals and safety issues during production and recycling. Participants ranked the impact category “health and safety” as the most important, followed by “social benefits and social security”.

For the two stakeholder groups local community and society “safe and healthy living conditions” were ranked as the most important factor. This is followed by “local employment”, “pollution of the environment” and “consumption of local resources”. “Stress on local infrastructure”, “shift of population demographics” and “research courses for the local community” were ranked as the least impactful factors.

For the stakeholder group value chain actors the manufacturers, electricity providers and clients were ranked as the most impactful actors along the value chain. Actors such as policy makers and recycling companies were ranked as the least impactful value chain actors.

For the stakeholder groups children and consumers “health and safety”, “environmental impact” and “consumer privacy” were ranked as the most impactful social factors. For the stakeholder group children “education” was identified as an important social factor as well, especially regarding the gamification aspect of smart textiles.

3.2 SOCIAL RISK ASSESSMENT OF THE EUROPEAN VALUE CHAIN

The social risk assessment of the bio-based SC production in Austria, France, Germany, and Greece reveals varying levels of risk impacting workers and societal conditions. Austria shows overall moderate risk, primarily in worker

health and safety, with fatal and non-fatal accidents in the manufacturing sector posing the highest risk, but they are still under the EU-27 threshold value for high risk (0.7) (eurostat, 2024). Austria exhibits a strong performance in collective bargaining and research and development (R&D) with risk scores under 0.3 (International Labour Organization, 2025). France faces medium to high social risks, with non-fatal and fatal accidents posing high risks between 0.7 and 0.8 (eurostat, 2024). Unemployment among people with higher education also represents a relatively high risk of 0.6 (eurostat, 2025b). Similar to Austria, France also exhibits a strong performance in collective bargaining by enforcing worker rights (European Parliament. Directorate General for Internal Policies of the Union., 2016). Germany excels in most indicators with social risk values below 0.5 in almost all indicators. The indicators freedom of association, collective bargaining and non-fatal accidents have a relatively high social risk compared to the other indicators in Germany (Labour Rights Index, 2025). Nevertheless, Germany maintains a strong industrial base and R&D investment (eurostat, 2024). Greece exhibits the highest social risk among the four production countries, with substantial challenges in worker rights, unemployment of people with advanced education and societal conditions. Unemployment of people with advanced education poses a risk of almost 0.8, due to skill mismatches (eurostat, 2025a) and collective bargaining has a risk of 0.7 (European Parliament. Directorate General for Internal Policies of the Union., 2016). Worker rights are represented by the indicators vulnerability to modern slavery and working hours which have social risk values of 0.5 and 0.6, respectively (Poulimenakos et al., 2021).

3.3 SOCIAL RISK MAPPING FOR THE EUROPEAN AND GLOBAL VALUE CHAIN

The results of the social risk mapping show the varying degree of social risk in the four current production countries (Austria, Germany, Greece and France) and the potential production country (China) when producing on a global value chain. Overall, the results show that the European countries experience less social risk compared to China, with Greece experiencing the highest degree of social risk among the European countries. The social risk for two relevant sectors for SCs can be assumed to be the same in all indicators except for the overall country-sector risk of forced labour, where China experiences a medium risk in the automotive sector but a very high risk in the chemical sector.

Table 1: Social Risk Mapping of the four European value chain (Austria, Germany, Greece and France) and potential Global value chain (China) (adapted from the social risk mapping tool (SHDB, 2022)).

Social Risk Indicators	Austria	Germa	Greece	France	China
Risk of child labour					
Risk of forced labour					
Risk of human trafficking					
Risk of excessive working time					
Risks related to freedom of association, collective bargaining					
Risk of no paid annual leave					
Risks related to labour laws and labour conventions					
Unemployment level					
Risk of occupational toxics and hazards					
Risk of labour injuries and labour fatalities					
Risk to gender equality					

Risk to peace	    
Risk of corruption	    
Risk to democracy	    

Low risk:  medium risk:  high risk:  very high risk: 

In two of the 14 social indicators analysed in this study China experiences low social risk: “Risks related to labour laws and labour conventions” and “Unemployment level” but experiences very high risk in six indicators: “Risk of forced labour” (chemical sector), “Risk of human trafficking”, “Risks related to freedom of association, collective bargaining”, “Risk of occupational toxics and hazards”, “Risk to peace” and “Risk to democracy”.

Within the European countries Greece is the only one experiencing very high risk in the two social indicators “Risks related to freedom of association, collective bargaining” and “Unemployment level”. “Risk of no paid annual leave” and “Risk to gender equality” are the two indicators where Greece experiences low risk. Austria and Germany experience the lowest degree of risk with for indicators having medium risk and one having high risk, France has the indicators at medium risk and three indicators at high risk.

4. DISCUSSION

The transition to sustainable and socially responsible energy storage systems is critical for advancing electromobility and addressing the social challenges associated with SC production. By using multiple SLCA approaches the study identified key social risks and opportunities across the current European and a hypothetical Global value chain and provides valuable insights for stakeholders in the automotive and energy sectors.

The results of the workshop and the social risk assessments are confirmed by the literature on social assessments of batteries, with all of them highlighting the complex and multifaceted nature of social risks associated with battery and SC production and their value chains. Existing literature confirms that resource extraction is the life cycle stage associated with the highest social

risks, with social indicators such as labour right violations, unsafe working conditions and adverse impacts on the local community being the largest concern (Koesse et al., 2023; Popien et al., 2023; Souza et al., 2025). The prioritisation workshop consisted of mostly researchers involved in the development of the SC who prioritised consumers as the most vulnerable stakeholder group, this result is likely biased because the researchers focused on the potential risk exposure of the final product to consumers and not the production itself, which mostly impacts workers and local community.

The social risk assessment and mapping reveal substantial geographic variability in social risks, both within Europe and globally. Among the European countries studied, Austria and Germany exhibit relatively low social risks, while France faces medium risks, and Greece experiences the highest risks. Greece's challenges include high unemployment among educated workers, weak collective bargaining, and vulnerability to modern slavery (European Parliament. Directorate General for Internal Policies of the Union., 2016; eurostat, 2024, 2025a; Koesse et al., 2023). These findings align with broader research indicating that developed countries generally experience lower social risks compared to developing or emerging economies (Shi et al., 2023). When expanding the analysis to a global value chain, the inclusion of China highlights stark contrasts. While China demonstrates low risks in areas like labour laws and unemployment, it faces very high risks in critical indicators such as forced labour, human trafficking, occupational hazards, and risks to democracy and peace (eurostat, 2024; Poulimenakos et al., 2021). These results emphasize the importance of considering regional contexts and regulatory environments when assessing social risks.

The discrepancies observed between the social risk assessment and social risk mapping underscore the methodological challenges in SLCA. The choice of methodology, data sources, and indicators can significantly influence the results, as seen in the contrasting performance of France in different assessments (European Parliament. Directorate General for Internal Policies of the Union., 2016; eurostat, 2024). This variability highlights the need for standardized and transparent SLCA methodologies, such as those outlined by the UNEP guidelines (UNEP, 2020), to ensure consistency and comparability across studies (Koesse et al., 2023).

Data availability remains a substantial limitation in SLCA studies, particularly for upstream and downstream processes in less regulated regions. The reliance on generic or sectoral data rather than site-specific information can obscure social risks and leads to substantial levels of uncertainty in the results. Stakeholder involvement is critical for addressing these gaps and ensuring

that SLCA processes focus on the most relevant issues (Fürtner et al., 2021; Groß-Fürtner et al., 2023; Koese et al., 2023). Additionally, the method developed by Zira et al. (Zira et al., 2020) tends to exclude extremely high or low risk potentials, leading to more homogenous risk levels (Mair-Bauernfeind et al., 2024). Nevertheless, this method was still able to showcase potential areas of high risk indicating which areas should be focused on. Following the limitations of this study, the assessment cannot be used to identify product specific hotspots but is the first step to identifying the potential hotspots. However, addressing these challenges requires a holistic approach that integrates fair manufacturing practices, ethical sourcing, and robust worker protections throughout the value chain as well as data availability on a product level.

5. CONCLUSION

The findings from this study and the broader SLCA literature provide initial insights into the potential social risks associated with SC production in the five countries assessed. Due to the use of secondary and generic data, the results cannot depict the actual social risks associated with SC production but are able to identify potential social hotspots on a country- and sector-level. All four European countries perform relatively well in terms of social risk potential, indicating that developed countries are associated with relatively low social risks during production. The inclusion of China highlights the need for stringent due diligence and ethical sourcing practices to mitigate risks in areas such as forced labour and occupational hazards.

The findings highlight the importance of conducting early social sustainability assessments, even in the face of uncertain value chains and limited data availability, to guide the development of socially viable products. These initial results can serve as a roadmap for researchers, policymakers, and industry stakeholders, emphasizing the importance of aligning technological advancements with social responsibility to create a more sustainable future. The bio-based SCs represent a promising innovation for advancing social sustainability in electromobility. By using renewable resources, enforcing fair labour practices, and enabling social innovation next-generation energy storage systems can contribute to broader goals of equity and sustainable development. The results provide actionable insights for stakeholders in the automotive and energy sectors. By prioritising health and safety, social benefits, and local employment, policymakers and industry leaders can enhance the social sustainability of bio-based SCs.

ACKNOWLEDGEMENTS

This work was performed within the project ‘EMPHASIS’ funded by the European Union’s Horizon Europe program under grant agreement number 101091997 and under the COMET program grant number 892 416 funded by the Austrian Research Promotion Agency (FFG). AI-tools have been used for language polishing and to enhance readability.

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