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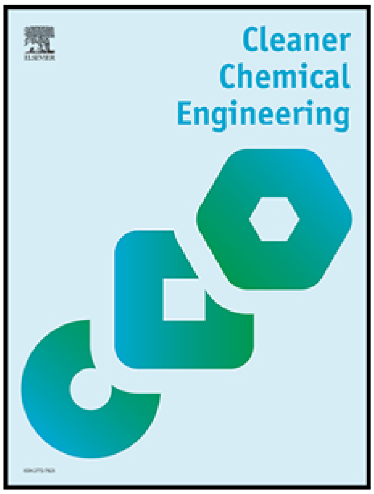

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How sustainability can get a competitive advantage: State of the Art for stationary battery storage systems

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Abstract

Stationary battery storage systems are becoming a critical energy infrastructure around the world. Therefore, responsible handling of battery materials is a fundamental precondition to avoid future social, environmental, and political conflicts. Global battery regulations support sustainable batteries to drive new business models on reuse, remanufacturing and recycling. With strict environmental market entry barriers, the EU will set minimum sustainability standards with the new EU-Battery Directive. The US Inflation Reduction Act provides financial incentives for a scale-up of the domestic battery industry. A hotspot analysis for the residential storage system VARTA.wall shows that a combination of reuse and recycling strategies can reduce the climate change impact by up to 45% and mineral resource use by up to 50% compared to initial battery designs. However, specific sustainability criteria and manufacturer-independent standards need to be set up by politics and industry organizations to bring the necessary technical and logistic infrastructure to the market. The challenge is to set up sustainability criteria strict enough to ensure responsible material handling but still allow cost-effective, practical solutions as well as affordable battery standards. Therefore, our analysis shows the limits of current and the need for future regulations to shift market incentives to sustainable batteries and their infrastructure.

Keywords

battery, regulation, stationary storage, life cycle assessment

1. Introduction

The stationary battery storage market is expected to experience significant growth in the coming years. According to various industry reports, the market size is projected to increase sevenfold until 2030, reaching a value of 32 billion dollars (BSW Solar, 2023; EUPD Research, 2023).

Consequently, the uptake for Energy Storage Systems (ESS) is attracting many suppliers, leading to a highly competitive market. Economic viability, technical performance, and safety considerations determine this sector's competitiveness. The new EU Battery Regulation aims to add sustainability considerations as another key performance indicator (European Union, 2023; Jannesar Niri et al., 2024; Melin et al., 2021). The challenges for this regulation include that ecological assessment methods need to be precisely defined, the use of rare and hazardous materials needs to be reduced, energy efficiency needs to be increased, and recycling or repurposing strategies need to be supported. A global standard mandating ambitious ecological considerations for producers will ensure that ESSs contribute to a cleaner and more sustainable energy transition.

Life Cycle Assessment (LCA) is the core methodology for assessing the environmental impacts associated with all the stages of the life cycle of a product, process, or service (Hellweg et al., 2023; Kralisch et al., 2018; Kralisch and Ott, 2017). LCA considers the full life cycle of a product, from the extraction of resources and the processing of raw materials, use phase, and recycling to the final disposal of remaining waste. For conducting an LCA, the principles and framework are given in ISO 14040 (ISO, 2021a), and requirements and guidelines are given in ISO 14044 (ISO, 2021b). By using these standardized frameworks, the credibility and comparability of the outcoming results can be increased. LCA has been promoted in different European directives as a robust quantitative tool in decision-making by producers and stakeholders.

However, to date, there is no consensus in the field of LCA on how the environmental impacts of batteries and ESSs should be analyzed and how the results should be presented (Tarroja et al., 2024). Studies use a variety of system boundaries, functional units, primary data sources, life cycle inventories, impact assessment approaches, and impact categories, which makes cross-comparisons between different technologies difficult and limits LCA's ability to create a feedback loop to early scientific research and technology development (Porzio and Scown, 2021). On a cell level, efforts have been made to harmonize life cycle inventory modeling (Peters and Weil, 2018).

Thus, in addition to ISO norms, European guidelines are being developed, particularly those that define the requirements for selected branches or products. On a chemical and material level, the proposed Safe-and-Sustainable-by-Design framework shall ensure that only environmentally sound chemicals are registered for use (European Commission, 2022a). The Product Environmental Footprint (PEF) is a multi-criteria methodology for life-cycle-based modeling and assessment of the environmental impact of material and energy flows and their associated emissions and waste streams of products and services. The method aims to standardize existing methods for LCA-based assessment of products by defining Product Environmental Footprint Category Rules (PEFCRs). We rely on the "PEFCRs for High Specific Energy Rechargeable Batteries for Mobile Applications" in this context. Even though PEFCRs for stationary applications so far do not exist, and as these rules are valid only for the application fields of e-mobility (e.g., e-bikes, EV, PHEV, cars, bus/trucks), ICT (e.g., tablets and phones, computers, cameras, games) and cordless power tools (e.g., drills, electric screwdrivers), it gives valuable hints that can be applied to the ecological assessment of battery systems in general.

Since about 70-80% of the final costs and environmental impacts are incurred at the initial development phase, a large potential for improvement exists, especially within the configuration phase of any process or product (Jeswiet and Hauschild, 2005). Thus, including LCA in the early design phases of product or process development has been on the research agenda for several years. While various methodological and practical challenges are emerging from using LCA at the early stage of development, there is an overall consensus on its suitability as a successful tool for evaluating ecological performance, resulting in a broad utilization of LCA as a decision-making tool in selecting processes, designing, and development, see, e.g. references (Ali and Gunasekera, 2023; Cucurachi et al., 2018; Kralisch et al., 2018; Ott et al., 2023, 2016, 2014; Van Der Giesen et al., 2020). As stated by Tarroja and colleagues, although regulation attempts to direct technology development toward ssustainability criteria, due to a lack of reliable information and robust as well as holistic evaluation frameworks, technology development runs ahead of regulation, even though deployment assessment is imperative for the sustainable production and use of batteries (Tarroja et al., 2024).

Here, we assess the current competitiveness of sustainable solutions in the ESS market from the perspective of an ESS producer. This assessment includes quantifying the environmental impacts of a reference case and scenarios with multiple reuse and recycling strategies as examples for so-calledR-strategies by simultaneously considering the current regulatory and economic situation for the largest markets. The article, therefore, provides a representative consideration of the sustainability-relevant strategic decision-making of ESS producers. Up to now, there are just a few publications on life cycle assessments of stationary energy storage systems available (Jasper et al., 2022). Most of them rely on secondary life cycle inventory data, especially for cells and peripheral components, and do not include end-of-life (EOL) considerations. Herein, a life cycle assessment based on primary data is performed, while simultaneously taking into account regulatory requirements and discuss their holistic impact on sustainability dimensions in a corporate context.

The impact of sustainability-oriented decision-making is particularly relevant as the United States and China massively fund domestic battery technologies. Further trade restrictions & import taxes are decoupling the supply chains to prepare for geopolitical escalation scenarios. Meanwhile, the EU is not entering funding competition but connecting European market access with ecological product requirements. It is unknown how the global supply chain will adapt to these conditions. The article further follows this structure:

1. This article will analyze sustainability- and battery-related laws and regulations in the EU, USA, and China.
2. A life cycle assessment case study of an ESS with multiple reuse and recycling strategies included, using a home storage system from VARTA, produced in Germany.
3. Finally, we will give decision support for industry and politics to make sustainability a competitive advantage.

2. Sustainability as competition – a policy review

This policy review summarizes battery-related environmental regulations that foster or steer sustainable battery production and management. Our goal is to identify acts and directives that provide a competitive advantage for more sustainable batteries on the market through financial incentives, minimum requirements, standardization, trade regulations, or other policy instruments. These regulations are embedded in a challenging competitive environment for batteries with different application fields from computer electronics and electric vehicles to stationary battery storage systems (SBSS). Table 1 summarizes key performance indicators for ESS in the field of lithium-ion batteries, their typical range, and core demands from the selected application fields. The values are not specific to SBSS and do not represent technical parameters of the VARTA.wall.

Table 1: Key performance indicators, typical ranges, and most demanding sectors and applications for each performance category.

Key performance indicator	Typical range of LIBs in general	Important demand
Gravimetric energy density	50-260 Wh/kg	Consumer electronics, long-range electric vehicles
Volumetric energy density	300-700 Wh/l	Consumer electronics, long-range electric vehicles
Voltage	3.0-4.2 V	All applications
Charge and discharge rate	Up to 2C for energy cells	Power tools, fast charging electric vehicles
Operation temperature	15-35°C	Safety, durability, and operation concerns for unusual operation conditions
Durability & performance, degradation and coulombic efficiency	Up to 2000 cycles, up to 99.99% coulombic effiiency	Electric vehicles, SBSS
Material costs	About 100 EUR/kWh	Low-budget vehicles, SBSS
Explosion and fire safety	qualitative	All applications
RoHS/REACH conformity	qualitative	All applications

The battery market has a long history of safety and waste management regulations. However, these are not the focus of this review because many of these regulations and standards focus on occupational health and safety, safety during transport and operation, or end-of-life waste products only. They emerge from long-established battery technologies containing toxic and hazardous substances and do not substantially differ between world regions.

We focus on US, EU, and China regulations, the largest battery markets, and important production regions. Comparing environmental regulations in these three world regions reveals different approaches toward fostering sustainable battery production, use, and recycling. Differing historical developments, legislative power distribution, strategic goals, and exposure to environmental problems can partially explain the differences.

2.1 Financial Incentives in the United States

The US, prominently in the form of the Inflation Reduction Act (IRA) of 2022 (117th Congress, 2022), focuses on reshoring raw material supply and battery production to the United States, supporting US-based battery production, raw material sourcing, and recycling with tax credits for battery producers and battery electric vehicle purchasers. The IRA includes "clean vehicle tax credits" for battery electric vehicles of up to 7,500 USD depending on the origin of Critical Minerals in the batteries and the origin of battery components. From 2027 onwards, half of the tax credits will only be granted if at least 80% of the critical minerals in the batteries are extracted or processed in the United States or a country with which the US has a free-trade agreement or recycled in North America. The feasibility and costs of such domestic sourcing and recycling targets for Critical Minerals also depend on the cell chemistry (Dunn et al., 2022; Trost and Dunn, 2023). From 2029, the other half of the tax credits are only granted if all the battery components have been manufactured or assembled in the United States. The IRA further grants an "advanced manufacturing production credit" for battery cells and modules of 45 USD per kWh battery capacity (35 USD for cell manufacturing and 10 USD for cell manufacturing). These tax credits will be gradually reduced from 2029 to 2032 (117th Congress, 2022). The Infrastructure Investment and Jobs Act of 2021 additionally provides funding for research, public investment, and private investment towards battery recycling processes and facilities. Still, it does not implement regulations on product- or producer-level (117th Congress, 2021). The Mercury-Containing and Rechargeable Battery Management Act of 1996 only regulates conventional, lead-acid, and nickel-metal hydride batteries that contain hazardous materials (104th Congress, 1996). The Resource Conservation and Recovery Act of 1976 doesn't mandate recycling facilities but addresses the disposal of batteries because of their hazardous material content. The Resource Conservation and Recovery Act enables the Environmental Protection Agency and states to regulate recycling based on protection from hazardous wastes and materials (94th Congress, 1976). In addition to national legislation, California sets its own standards on recycling efficiency for batteries through the Responsible Battery Act of 2022 (California Assembly, 2022). There are, however, no national requirements for recycling efficiencies.

The United States emphasizes reshoring supply chains for low-carbon technologies like batteries. While it acknowledges the importance of renewable electricity and energy storage to meet climate targets, the precise legislative measures lead to strong financial incentives to buy domestically produced products and components, particularly battery electric vehicles, batteries, and virgin or recycled critical minerals. US laws do not prohibit selling products that do not comply with the regulations (except for batteries containing hazardous materials). Still, the incentives are strong enough that the market shares are or will be significantly altered toward domestically produced cars and batteries. The United States does not have extended producer responsibility for electric vehicle batteries. Furthermore, the US does not make additional obligations to prove the environmental and social sustainability of purchased components or raw materials – it is assumed the environmental benefits will materialize due to the scale-up of low-carbon technology production overall, particularly because of the regionalization of the supply chains.

2.2 Market Entry Requirements in the European Union

The EU, in contrast, makes much more detailed and ambitious requests on the environmental sustainability of batteries with its new EU Battery Regulation. It sets various targets for electric vehicle batteries, light means of transport batteries, rechargeable industrial batteries, and portable batteries of general use (European Union, 2023). The requirements of the new battery regulation range from sustainability and safety requirements, over labeling and marking to managing waste batteries and a digital battery passport (Berger et al., 2022). Some articles of the regulation apply only to selected types of batteries. A delegated act based on the sustainability requirements of the regulation will establish a methodology for calculating the carbon footprint of the battery, followed by carbon footprint performance classes and, ultimately, a maximum threshold for the declared life cycle carbon footprint value of batteries. Another delegated act will establish a methodology for calculating the percentage share of materials in the batteries recovered from battery manufacturing or post-consumer waste. For cobalt, lead, lithium, and nickel, minimum percentage shares for these recycled contents are defined for each battery model per year and per manufacturing plant. Another delegated act will establish mandatory minimum values for batteries' electrochemical performance and durability parameters to avoid adverse incentives between environmental and technical performance. Portable batteries and light means of transport batteries will need to be removable and replaceable. SBSSs must comply with safety parameters for corresponding hazards. Labels and QR codes printed or engraved visibly, legibly, and indelibly on the battery provide information on cadmium and lead content, the battery passport, conformity with the regulation requirements, and recycled content for cobalt, lithium, nickel, and lead. The battery management system shall contain read-only information on the state of health and expected lifetime of batteries. The waste management requirements specify the extended producer responsibility, collection targets for waste batteries, targets for recycling efficiencies, and recovery of materials. Finally, a digital battery passport must be available and accessible, containing all relevant information on the battery's performance, safety, and environmental parameters (European Union, 2023). This battery regulation was finalized in 2023, and its parts will come into force step-by-step over the next few years. It will have global implications because any battery sold on the European market needs to fulfill these requirements (Melin et al., 2021). That means even battery producers on other continents will have to adapt their batteries to comply with the EU battery regulation if they want to sell them in the EU market.

The instrument to foster sustainable batteries used in the EU battery regulation is predominantly a set of minimum criteria that need to be matched by battery producers. The battery regulation creates an entry barrier to the market for insufficiently sustainable batteries. From a sustainability science perspective, the question arises of how battery producers globally will react to this regulation. Battery producers focusing on the EU market are rushing to fulfill the requirements set in the regulation. However, mandatory minimum thresholds and a set of obligatory criteria that need to be matched for any battery can incentivize companies to fulfill the requirements with the least effort or the lowest surplus costs versus current non-compliant batteries.

Further sustainability improvements going beyond the requirements are not incentivized. For example, there is no incentive in the battery regulation that would provide a competitive advantage for battery producers that have even higher recycled content for cobalt, lithium, nickel, and lead contained in their batteries than what is set as the minimum requirement. For the carbon footprint, there is at least the possibility that batteries with an even lower life cycle carbon footprint value can be advertised and labeled with a carbon footprint performance class even better than the mandatory maximum threshold. Details can only be discussed once the corresponding delegated act is available.

It is unclear whether battery production for non-EU markets will also become more sustainable due to the EU battery regulation. On the one hand, minimum recycled content for EU-targeted batteries could funnel waste materials into their production and reduce the availability of recycled materials for non-EU-targeted batteries without affecting the global average recycled content. In this case, this part of the battery regulation would not lead to increased sustainability. On the other hand, it would only make sense to use the tools and technologies used to be battery regulation compliant, like the battery passport, in all batteries, be it for the EU or non-EU market, to spread the development costs on as many products as possible. That said, the overall requirements of the EU Battery Regulation are ambitious and challenging, and the size of the EU market and the complete inability to sell non-compliant batteries provide many incentives for increased sustainability in battery production. Multiple large-scale, public-funded research projects are underway to facilitate the carbon footprint, circular economy, and battery passport compliance of future batteries.

In addition to the Battery Regulation, the EU has also adopted a Taxonomy on Sustainable Finance (European Union, 2020), where the Climate Delegated Act defines that battery production activities that "manufacture rechargeable batteries, battery packs and accumulators (and their respective components), including from secondary raw materials, that result in substantial GHG emission reductions in transport, stationary and off-grid energy storage and other industrial applications" are considered sustainable because of their impact towards climate mitigation as long as they do no significant harm regard the other criteria climate change adaptation, sustainable use and protection of water and marine resources, transition to a circular economy, pollution prevention and control, and production and restoration of biodiversity and ecosystems (European Commission, 2021a). This classification as sustainable according to the Taxonomy shall enable better financing opportunities and thereby support the respective economic activities. Most battery producers will likely fulfill these climate change mitigation criteria for mobility and stationary applications.

One reason the European Union uses regulations with minimum requirements rather than tax benefits and subsidies is the limited financial autonomy of the EU governing body. Taxation and subsidies are still mostly focused on the level of member states, which is why the EU cannot use the same methods as the United States with the tax credits of the IRA.

2.3 Less transparent regulations in China

Several smaller legislative acts have been published in China recently (Bird et al., 2022; Siqi et al., 2019), setting new targets for battery safety, performance, and environmental impacts. The Interim Measures for the Management of Recycling and Utilisation of New Energy Power Vehicle Battery of 2018 call for battery manufacturers to adopt design-for-dismantling, provide disassembly and recycling information, and as much as possible recycled materials usage without specifying what is possible (MIIT, 2018a). The Measures for the Administration of New Energy Vehicle Power Battery Ladder Utilization of 2021 introduced, among others, a new energy vehicle national monitoring and power battery recycling traceability integrated management platform where management measures are coordinated that foster the traceability of supply chains and the recycling of battery materials (MIIT, 2021a). For multiple years, the Chinese government has supported scaling the battery and battery recycling industry with the Pilot Work on Recycling and Utilization of Power Battery for Electric Vehicles of 2018, which included establishing a recycling system for new energy vehicle power batteries and an extended producer responsibility system. The pilot plan explicitly mentions the exploration of diversified business models to meet the market demand and maximize the value of resource utilization and the establishment and improvement of policy incentive mechanisms to promote power battery recycling (MIIT, 2018b). The Lithium-ion Battery Industry Specification Conditions 2021 are designed to promote China's lithium-ion battery industry, improve quality, technical innovation, and safety, and reduce production costs. Environmental aspects are covered by formulating requests that battery producers measure and reduce energy consumption, increase resource recycling, and perform environmental impact assessments, environmental hazard, and occupational health risk assessments (MIIT, 2021b). Table S1 in the Supplementary Material summarizes battery-related policies and standards in China since 2010.

However, the wording of these various Chinese regulations is generally vague, minimum thresholds and financial incentives are rarely mentioned, and the implications for battery producers outside of China seem difficult to assess. Foreign companies are also typically not involved, let alone informed, about the policymaking process, leading to uncertainties regarding future environmental standards and regulations for foreign battery producers.

3. Life cycle assessment case study

The Life Cycle Assessment calculations are specific for the stationary battery storage system called VARTA.wall (VARTA, 2023). This new-generation product is a residential storage system with a market launch in 2024. The selected configuration comprises a master unit, modules, and a base unit. The base unit provides the form and structure of the whole system, the master unit contains the energy and battery management systems, and the modules contain the battery cells with a slave BMS. The modules contain round cells in the 21700 formats, which are 21 mm in diameter and 70 mm in length. The system is produced by a large German battery producer, VARTA, to provide a slim, easy-to-install solution for households. Table 2 shows a picture of the VARTA.wall and lists its main components.

Table 2: Assembly groups and main components of the VARTA.wall stationary battery storage system.

VARTA.wall	Assembly group	Main components	Manufacturing location
	Master Unit	Housing	Germany
		Energy management system (EMS)	
		Battery management system (BMS)	
		Electric connectors	
		Cables	
		Auxiliaries (sealing, adhesive, etc.)	
	Module (2x)	Housing	Germany
		Cell holder	
		NCA cells	China
		Slave BMS	Germany
		Electric connectors	
		Metal parts (screws, etc.)	
		Auxiliaries (sealing, adhesive, etc.)	
	Base Unit	Housing	Germany
		Electric connectors	
		Metal parts (screws, etc.)	
		Auxiliaries (sealing, adhesive, etc.)	

Figure 1 shows the mass share of assembly groups and main components of the VARTA.wall. The modules have a mass share of 85 %, followed by the master unit with 10 % and the base unit with 5

%. The mass is dominated by the battery systems (58 %) and the housing elements of all assembly groups (combined 31 %). In contrast, electronic equipment, including the BMS, connectors, and cables, as well as screws, adhesives, and sealing, counts for less than 10 % of the weight.

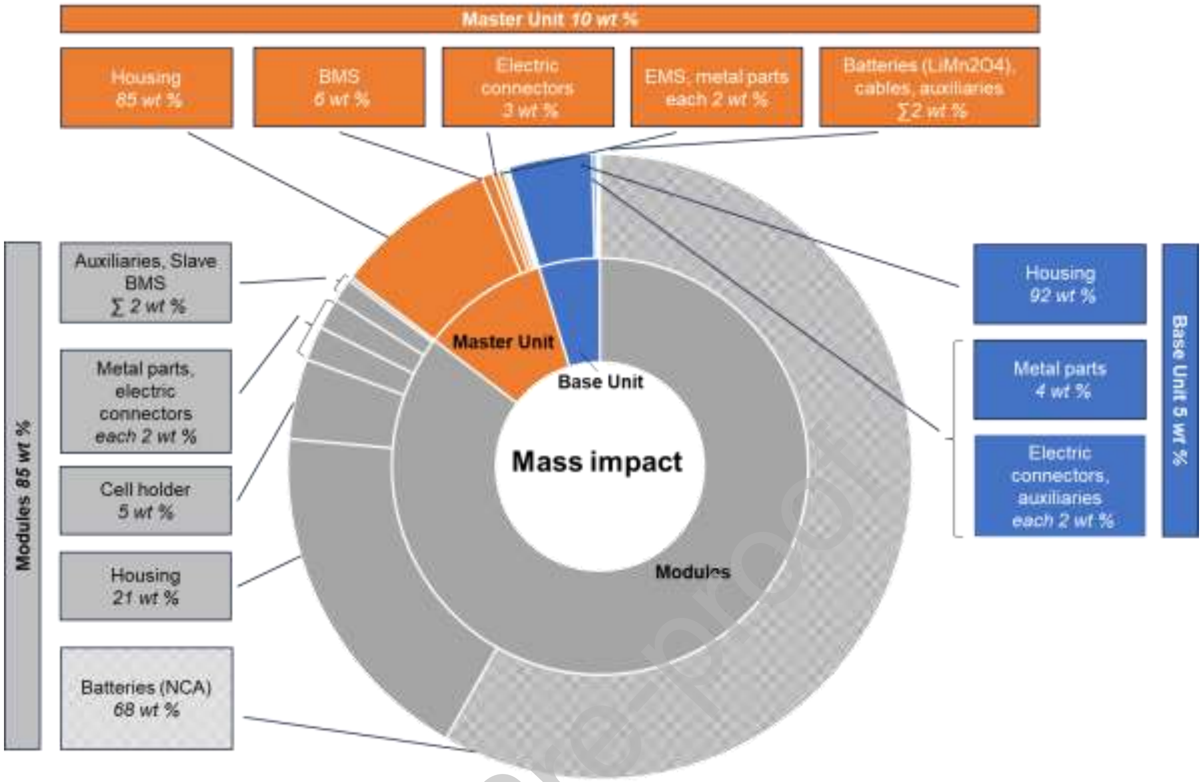

Figure 1: Share of masses of assembly groups (inner circle) and their main components (outer circle) to the stationary battery storage system.

3.1 Hot Spot Screening according to DIN EN ISO 14040/14044

Goal and Scope. This study aims to conduct a life cycle assessment during the research and development stage of a stationary battery storage system. The assessment encompassed an ecological screening of the production, recycling, and reuse options following DIN EN ISO 14040/ 14044. In line with the EU Battery Regulation (European Union, 2023), the use phase of the batteries is excluded from the life cycle assessment. We employed the EU-developed Product Environmental Footprint 3.1 life cycle impact assessment method to achieve this objective, incorporating the circular footprint formula for end-of-life modeling recommended therein.

The functional unit was defined as per kWh of battery capacity in terms of lifetime energy throughput. However, as the assessment is performed in a relative context, assuming comparable performances for each scenario, the functional unit of "per storage system" was also selected.

Life Cycle Inventory. The life cycle inventory was modeled with the software Umberto 11 (iPoint, 2023) and the ecoinvent 3.9.1 life cycle inventory database (Wernet et al., 2016). Background inventory data concerning the supply of raw materials, energy, and transport processes were integrated. As far as possible, life cycle inventory data were taken from ecoinvent (cradle-to-gate related) or literature sources (end-of-life related) to gain fast insights into ecological hot spots and optimization potentials, especially as specific supplier information is often missing.

However, in the case of battery cell supply, generic ecoinvent datasets were adapted to the cell characteristics of the batteries considered herein to estimate the environmental impacts of components more accurately. The battery cell under investigation is a cylindrical Nickel Cobalt Aluminum (NCA) cell supplied from China. The ecoinvent dataset "battery cell production, Li-ion, NCA (CN)" was adapted accordingly, e.g., the cell used herein comprises a cylindrical steel housing. In contrast, the ecoinvent dataset implies a pouch cell housing. Furthermore, upstream processes were aligned so that the material composition matches the cell specifications. Energy requirements for cell manufacturing were left as is. Since the cell is produced in China, the Chinese electricity mix was used, and other inventory data was changed to Chinese origin, wherever possible. Due to the unavailability of precise upstream transportation data, "market" values with generic transports were implemented as input data for cell manufacturing.

Regarding storage manufacturing, the study considers primary information from VARTA. As the ecological assessment of the storage design is currently placed in the R&D phase, production data, i.e., the final assembly of the parts supplied by subcontractors, are unknown. As Varta is using renewable energy sources, and as the demand for auxiliaries and solvents can be assumed to be quite low compared to upstream and downstream processes, neglecting the same can be justified in the framework of this screening analysis. As far as possible, the materials supply in the countries of origin specified by Varta was considered. Additional technical specifications of the NCA cell and the storage built-up are provided in the supplementary information. Modeling does not only include material supply but also processing steps such as injection molding or metal working manufacturing processes to make a semi-manufactured product (e.g., metal sheet, plastic granule) into a final product (e.g., housing, cell holder). Regarding the housing elements, different aluminum alloys are used, for which dedicated life cycle inventory modelling activities were performed. According to the supplier, the aluminum used is of 100 % secondary nature. Some smaller parts (e.g., label, antenna, power switch) and packaging were neglected due to their comparably low mass and ecological impact. Table 3 summarizes the main assembly groups, components, and corresponding ecoinvent data sets.

Table 3: Main components and corresponding background life cycle inventory datasets in the ecoinvent database.

Main components	**Life cycle inventory datasets (ecoinvent 3.9.1)**
Batteries	battery cell production, Li-ion, LiMn2O4 battery cell production, Li-ion, NCA (adapted from ecoinvent 3.9.1)
Housing (cover plate, front cover, separating wall)	different aluminium alloy production (adapted from ecoinvent 3.9.1, data set aluminium alloy production, AlMg3) glass fiber reinforced plastic production, polyester resin, hand lay-up
Cell holder	acrylonitrile-butadiene-styrene copolymer production polyester resin production, unsaturated
Metal parts (screws, spring plates)	steel production, chromium steel 18/8, hot rolled copper production, cathode, solvent extraction and electrowinning process
Connectors	electric connector production, peripheral type buss
Sealing/adhesives	adhesive production, for metal; silicone product production; synthetic rubber production
EMS/BMS	printed wiring board production, surface mounted, unspecified, Pb free
Cable	cable production, unspecified

After the use phase, different reuse and recycling scenarios could become possible. Because design changes would hinder the complete reuse of most constructional or electronic components, scenario

"Reuse Level 1" only considers remanufacturing and reusing the base and master units for a second life cycle. Hypothetically, if the design changes allow scenario "Reuse Level 2" further includes remanufacturing and reusing all module components except the NCA cells and cell holder. In a final scenario, namely "Best Case", the multiple reuse options are combined with hydrometallurgical recycling of the NCA cells. Therefore, state-of-the-art hydrometallurgical recycling routes for the NCA cell were considered. Data on the end-of-life phase was compiled from the EverBatt 2023 Model (Argonne National Laboratory, 2023). Table 4 summarizes the reuse and recycling scenarios. The supporting material lists the full life cycle inventory.

Table 4: Definition of scenarios considered in the Life Cycle Assessment for the VARTA.wall.

Scenario	Description
Base Case	Battery storage system VARTA.wall as produced
Reuse Level 1	Reuse of base unit and master unit
Reuse Level 2	Scenario "Reuse Level 1" + reuse of module, except cell holder and NCA cells
Best Case	Scenario “Re-Use Level 2” + hydrometallurgical recycling of NCA cells

Life Cycle Impact Assessment. In the context of adhering to EU-compliant LCA practices, the PEF 3.1 method was chosen. According to the recommendations of the Product Environmental Footprint Category Rules for rechargeable batteries by the European Commission (RECHARGE, 2018), the most relevant impact categories for the environmental analysis of batteries are climate change (in the following, also referred to as greenhouse gas or GHG impact), resource use (fossil energy carriers and minerals/ metals) and respiratory inorganics (also known as particulate matter). Therefore, this study specifically targeted these categories in its analyses.

Regarding recycling, the methodology provided by PEF for calculating the End-of-Life phase was considered. When applying the PEF method, life cycle assessment practitioners must employ the circular footprint formula (European Commission, 2021b) for assessing the End-of-Life phase, where recycling credits rely upon a so-called "A-factor". The A-factor reflects market realities and depends upon the market's saturation with secondary material. The lower the A-factor, the higher the market's saturation with recycled material (i.e., the lower the demand for new recycled material). Thus, more credit is given to the use of secondary goods. On the other hand, the higher the A-factor, the less saturated the market, and more credits are given to the recyclability of a product. In PEF studies, the A factor values shall be in the range $0.2 \leq A \leq 0.8$ (European Commission, 2021b), and a few material-specific A values are published by the EU (European Commission, 2022b). No A-factor was specified for batteries, but instructions were given to use the individual A-factors of the recycled materials. These were followed subsequently.

Results. Figure 2 depicts the share of GHG impact of the assembly groups, i.e., master unit, base unit, and modules, and their main components, to the SBSS. The GHG impact of the modules is 79 %, followed by the master unit with 20 % and 1% for the base unit. The overall climate change impact is dominated by the battery systems (63 %), energy and battery management systems (16 %) and the housing elements of all assembly groups (12 %). The effect of the latter would have been much higher if no secondary aluminum had already been used. Compared to mass-related impacts, see Figure 1, slight deviations can be recognized due to the higher ecological impact of the master unit's EMS and BMS, contributing to the overall climate change impact by 16 %. Other equipment with a negligibly low mass share, e.g., connectors, cables, as well as screws, adhesives, or sealing, contribute less than 5 % to the overall climate change impact. Although this is an initial hot-spot screening sourced from partially secondary life cycle inventory data, the conclusion that can be drawn is quite clear and robust. The highest environmental benefits will result if the supply of batteries, battery management systems, and housing elements are rethought in the context of material choice or – potentially more likely – circular economy concepts.

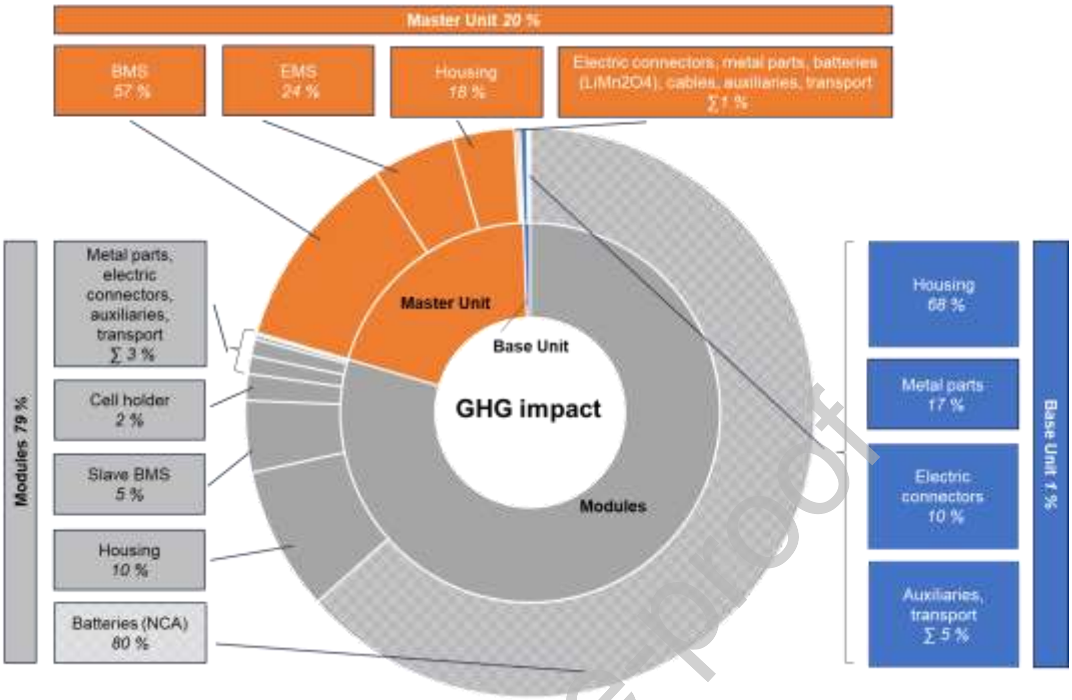

Figure 2: Share of GHG impact of assembly groups (inner circle) and their main components (outer circle) to the stationary battery storage system.

Figure 3 shows the relative impact of the assembly groups and batteries on all considered environmental impact categories: climate change, particulate matter, fossil fuels, and mineral resource use. In general, the trends observed for climate change remain. However, the impact of master unit supply to the category "resource use, minerals and metals" is increasing and in the range of the impact of NCA battery supply due to the ecological backpack connected with the supply of master unit's battery management and energy management systems.

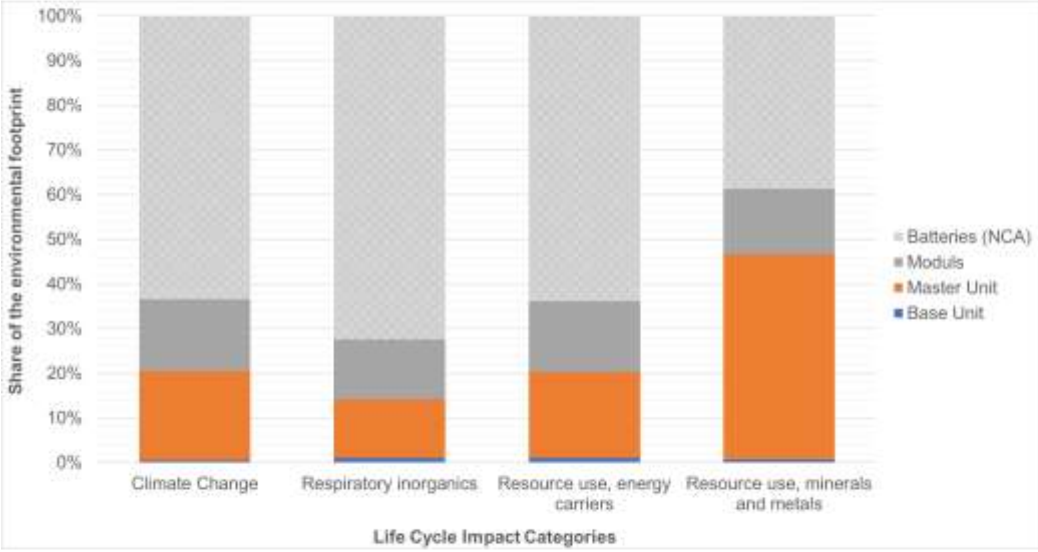

Figure 3: Share of the environmental impact (climate change, respiratory inorganics, resource use) of assembly groups and batteries to the stationary battery storage system. Scaled effects.

Figure 4 visualizes the environmental impact of all main ecological drivers, i.e., NCA batteries, master unit battery management system, master unit energy management system, module housing, and master unit housing, compared to their mass impact, emphasizing the resource use impact (minerals and metals) of the electronic system (BMS, EMS) despite their comparably low mass share.

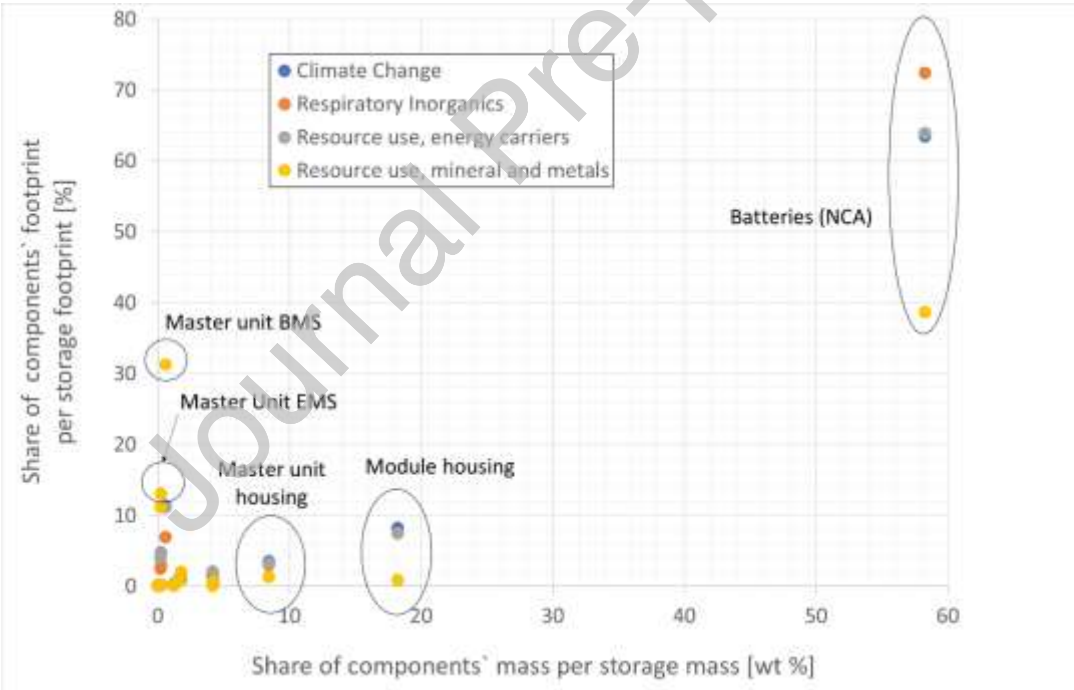

Figure 4: Share of masses and environmental impacts (climate change, respiratory inorganics, resource use) of the stationary battery storage system components.

Consequently, if applying the reuse and recycling strategies given in Table 4, climate change impact reductions of up to 37% can be achieved by reusing the base unit, master unit, and modules (except cell holder and NCA cells) and recycling NCA cells via hydrometallurgical recycling (Figure 5). Jasper and colleagues came to similar conclusions (Jasper et al., 2022); dependent on the cell type, ESS show significant GWP benefits from recycling, being up to 16% of the original impact caused by the production of the systems, whereas the main share is due to cell recycling (up to 85 % in case of NMC cells). As the focus herein is on NCA cells, a direct comparability is not given, however, the trends observed are similar.

A component-level display of the savings of the best case for climate change and resource use of minerals and metals can be found in the Supplementary.

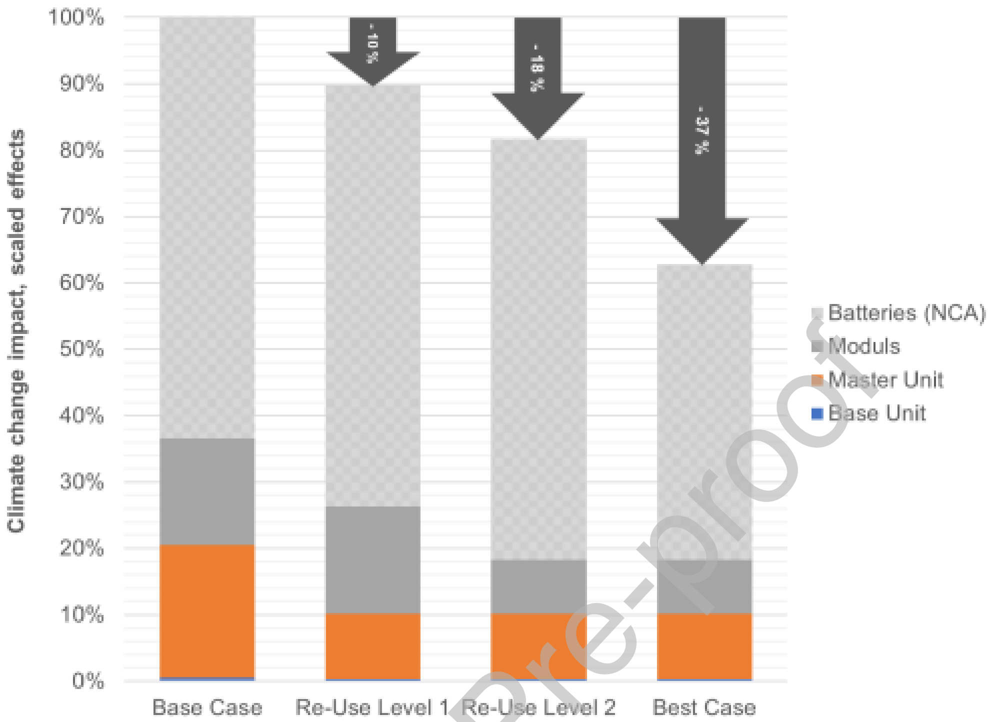

Figure 5: Climate change impacts and contribution of assembly groups in different reuse and recycling scenarios (see Table 3). Scaled effects.

4. Discussion, business implications and policy recommendations

According to the results, decision support for industry and politics are going to be discussed to make sustainability a worldwide competitive advantage. In the following business implications as well as recommendations for policy and battery stakeholders have been derived.

The CO2 emission reduction potential in the 4 scenarios does require a capable take-back system with an integrated logistics and remanufacturing process. In addition to these technical requirements, the end customer also needs an incentive to go with second-life components.

By design the modular storage system from VARTA is suitable for Reuse Level 1 as the master and base unit can be easily separated from the battery module, therefore only minor changes are needed on the battery side. For Reuse Level 2 manufacturer independent standards need to be set up to enable cost-efficient disassembly or remanufacturing of various storage systems. As residential storage systems do have a product lifecycle of more than 10 years manufacturer specific solutions cannot be set up in cost cost-effective way. These standards need effective solutions to tackle the 4 main cost drivers for sustainable batteries.

Logistic Costs. Different logistic processes must be organized when the ESS reaches its EOL to enable a recycling or remanufacturing scenario. Currently, there are different Battery Take-back systems established in every region. Within these systems, certified providers manage the logistics and recycling process compliant with national laws. By implementing a resource strategy, there will also be the need to sort out the battery into parts suitable for re-manufacturability or NOK components that need recycling or even disposal. Additionally, certified re-manufacturers must have strong know-how to work with heterogeneous SBSS. This increased complexity of testing, sorting, and heterogeneous supplier requirements will significantly drive recycling costs.

Remanufacturing costs. Certification of SBSS is dependent on the manufacturing process and the used components. A remanufactured SBSS, therefore, needs a new certification because new processes & components will be necessary.

Design costs. "Cell-to-Pack" manufacturing concepts reduce the number of components in a battery system and are frequently realized by gluing the battery cells without an additional cell holder. These designs reduce the costs of the battery module by up to 10%. However, this cost-saving potential needs to be reviewed if remanufacturing or automated disassembly processes are considered. Moreover, modern hydrometallurgical recycling processes are very sensitive to impurities in pretreatment steps. Therefore, cells with fluorine might not be suitable for this recycling route and PVD and PTFE binders below 1 wt.% are very common in LIB technology. Therefore, the requirement on cell level has an impact on recyclability.

Incentive to End-Costumer. Also, a sustainable ESS must be sold to the end consumer. Studies show that price, safety, and independence are the main drivers of ESS purchasing. Therefore, sustainability needs to be balanced by the OEM with the other decision criteria. Political framework conditions massively influence this balance.

In Europe, the biggest lever to enhance sustainability is the EU Battery Regulation and the option to define the minimum sustainability standard for an EU market entry. However, this product requirement regarding raw material, performance data, carbon footprint, and recyclate requirements will drive further costs on technical products, manufacturing, and sustainability reporting. Ultimately, the industry will be pushed to find a way to fulfill the minimum standard at the lowest cost.

In the USA, the IRA gives a 30% tax credit for domestic investments. If components and materials are sourced inside the US, there is a potential to get up to a 50% tax increase. For cells, these subventions can be summed up to 35 USD/kWh, 10 USD/kWh for the module, and even more credits on the power electronic side. If an OEM can build an ESS mainly based on domestic materials and components, tax credits will fund 50% of the initial product costs. As a result, the market participants are looking for the cheapest way to fulfill the criteria for the maximum tax credit. As a result, we see increased investments in primary and secondary battery material production. As the availability of domestic primary materials is limited, it can be expected that there will be a growing demand for reused and recycled components if the costs are competitive with products with no tax credit option. Table 5 summarises the regional incentives for sustainable batteries.

Table 5: Comparision of incentives for sustainable batteries through regulations in the EU, USA, and China

Regional incentive Cost for Actions	**EU**	**USA**	**China**
Design Costs	EU-Battery Regulation: market entry restrictions	Tax Credit: 35 USD/ kWh for domestic produced cell capacity +	No information
Logistics Costs			
Remanufacturing Costs			
Incentive End-Costumer to go with Reuse Hardware	EU-Battery Pass:		

	Transparency on battery performance + storage life	10 USD/ kWh for produced module capacity	

To further enhance the relevance and impact of the Life-Cycle-Assessment method Table 6 summarizes the policy recommendations for key stakeholders, like federal, state and governmental agencies, Battery Industry, Manufacturers and Designers as well as Battery System Integrators and Business. Actionable measures and potential implementation challenges are provided to give specific policy suggestions in the field of battery reuse and remanufacturing. Potential trade-offs show the responsibility for sustainable materials and processes.

Table 6: Policy recommendations and potential trade-offs for worldwide standardized battery R-strategies (in addition to Tarroja B. et al., 2024)

Key Stakeholder	**Actionable Measures**	**Implementation Challenges**	**Potential Trade-Offs**
Federal, State, Governmental Agencies (Politics)	Financial incentives, worldwide standardization with minimum requirements and trade regulations with policy instruments	Incentivizing the build-up of infrastructure for reuse and remanufacturing of batteries and battery components, e.g. Business Start-ups Worldwide thresholds for Carbon Footprint reductions Standardized Circularity rules	National regulations stricter than in other regions can lead to industry not producing, investing, or selling in that region with negative economic effects.
Battery Industry, Battery Manufacturers and Designer and Battery System Integrators	Transfer of political regulations, standardization and transparency	Worldwide thresholds for Carbon Footprints	If minimum requirements are too strict, growth of the ESS market can be slowed, negatively affecting the shift to low-carbon technologies globally and leading to higher greenhouse gas emissions.
Battery Industry, Battery Manufacturers and Designer and Battery System Integrators Businesses	Integrate Life-Cycle-Assessment into decision-making:	Definition of ecological assessment methods, reduction of use of rare and hazardous materials, increase of energy efficiency and support of recycling strategies (esp. Reuse and remanufacturing)	Implementation of Life Cycle Thinking requires additional skilled and trained staff for assessments in times of increased demographic competition for staff hiring.

5. Conclusion

Batteries are important in the future energy system and are therefore politically supported in every region. In the EU, the main lever of policymakers is a potential market entry restriction for batteries that are less sustainable and less transparent regarding important data. These market entry criteria are laid out in the EU Battery Regulation of 2023. In the US, the tax credits for battery producers and purchasers linked to batteries and battery materials from the US and neighboring or partnering countries are the key incentives given. Chinese regulations are more scattered and less transparent but envision increasingly strict sustainability and circularity of batteries.

The Life Cycle Assessment case study for a stationary battery storage system of a large German producer showed substantial reduction potentials for the carbon footprint and other environmental impact categories if housing and other parts of the base and master unit are reused, and the battery cells are recycled. In the EU, these reductions in the Carbon Footprint need to be achieved to ensure that future thresholds are met. In the US, such sustainability efforts can be incentivized by the tax credits. In China, specific requirements for recycled content or local sourcing may still be further defined, or sustainability-related requirements for Chinese producers can also be defined by their export ambitions to the EU market. However, whether these diverging political approaches lead to a competitive advantage for even more sustainable products than what is required by regulations as the minimum is questionable. For that, additional modifications in the various regulations would need to be laid out.

Our work also highlights the need for more transparency in policymaking. There is much more information available for the EU Battery Regulation (and in future its delegated acts) as well as the Product Environmental Footprint Category Rules and the Circular Footprint Formula to assess the minimum sustainability needs for new battery systems and to quantify the environmental impacts in a harmonized way. The US regulations only look at the material origin or the supply chain and differentiate between materials and batteries eligible for tax credits. Carbon footprints and environmental impacts of battery production are not part of the US legislative framework. The Chinese regulations have more goals and targets for the markets to meet, and the precise consequences for battery producers are more challenging to identify. A stationary battery storage system producer intending to put a more sustainable product on the market faces three entirely different regulation types.

If regulators are serious about the implementation of an ambitious circular economy for batteries at high levels of the waste hierarchy, the current regulations need to be improved in all regions. Improvements need to focus on incentivizing the build-up of infrastructure for reuse and remanufacturing of batteries and battery components, not primarily recycling. Without those incentives, the substantial environmental benefits of ambitious reuse, remanufacturing, and or recycling for batteries might not be realized. Researchers interested in the global environmental impacts of battery production and the future development of these due to more circularity (Barkhausen et al., 2023) should consider this while quantifying the circular economy potentials in their analyses.

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Supplementary Material

Additional Supplementary Material is available in the online version of this manuscript.

Author contributions

Benjamin Achzet: Conceptualization, Supervision, Writing
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Rica Fleiner: Data curation, Project administration, Visualization
Marvin Gornik: Data curation
Andrea Thorenz: Conceptualization, Writing – review & editing
Christoph Helbig: Formal analysis, Methodology, Writing

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: