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Research Paper

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Can a growing battery industry remain within planetary boundaries?

The rapid growth of the battery industry leads to a high demand for critical raw materials, an increasing amount of battery waste and environmental impacts along the value-chain. Several life cycle assessments have compared the relative environmental impacts of different battery technologies, production processes, or locations. However, an assessment of the environmental impacts of batteries on a planetary scale is missing. Therefore, we provide a connection between the environmental impacts of the potentially circular battery value chain and the planetary boundaries framework. Transgression of planetary boundaries will lead the Earth down an unstable path, which should be avoided. While the use of batteries in the automotive industry has significant positive impact on the environmental footprint, the battery production will clearly transgress its assigned share of the safe operating space in three planetary boundaries in 2030, 2035 and 2040 on its current trajectory. Consumption of critical raw materials accounts for most of the planetary footprint, encouraging the development of sodium-ion batteries and circular economy strategies. Alongside high recycling rates, the consequent implementation of process innovations, such as dry coating and direct lithium extraction, and the use of renewable energy will reduce the transgression of planetary boundaries. Still, further efforts are required to bring the battery industry in line with its safe operating space for phosphorous cycle and climate change. To avoid the prospect of strict policy interventions, our work encourages the fast-growing battery industry to assess innovations and demand projections through a planetary boundary lens.

1 Introduction

Since the Paris Climate accords were signed in 2015, government and industry have increased their efforts to limit climate change to 2°C compared to pre-industrial levels (The Economist , IPCC 2023). While current global investments in low or negative carbon dioxide (CO2) emission technologies still fall short of the required levels, some ground has been gained (International Energy Agency 2023, The Economist 2023). Electrification of the transport sector, mostly by switching to battery electric vehicles (BEVs), is a strategic aim of major car manufacturers (Kwade et al. 2018,

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Schmuch et al. 2018, Duffner et al. 2021).Government schemes, such as the proposed, even though controversial, ban of internal combustion engine vehicles (ICEVs) from 2035 by the European Union, have created further incentives to increase production of BEVs (European Parliament 2023). Charged with renewable, or other low-carbon electricity, lifecycle CO_2 emissions associated with BEVs are lower than for petrol-fueled cars (Ellingsen et al. 2016). On the other hand, concerns about the high levels of critical raw materials required for battery production or environmental issues associated with mining or disposal of batteries present challenges (Herrington 2021, Du et al. 2022).

Experts estimate that the annual battery production will reach 5,400 to 6,800 GWh per year by 2030, up from 1,800 GWh in 2024 (International Energy Agency 2023, Porsche Consulting GmbH 2023). Innovations in processing technology, such as dry coating, and changes in battery material composition, towards sodium-ion batteries (SIBs), will likely reduce the CO_2 emissions associated with future battery production (Degen et al. 2023). In addition, recycling of end-of-life batteries is expected to reduce the environmental impacts and raw material requirements of the growing battery industry (Baars et al. 2021, Gutsch and Leker 2024). Life cycle assessments (LCAs) have been used to compare the environmental impacts of different battery material choices, production technologies, or end-of-life treatments (Peters et al. 2017). The first LCAs of lithium-ion batteries (LIBs), which currently account for most batteries used in BEVs, were conducted in the early 2000s (Peters et al. 2017). Today, numerous LCAs exist, covering novel material choices, production technologies, and battery recycling (Arshad et al. 2022).

Life cycle assessments are a useful method for comparing the relative environmental strength and weaknesses of different products used for the same function (International Organization for Standardization 2006). But, communication with decision-makers and inferring global strategies from LCAs is challenging (Ryberg et al. 2018). Here, the planetary boundary framework (PB) captures more readily whether a certain activity improves or reduces the chances of staying within Earth´s safe operating space (SOS) (Rockström et al. 2009). Nine planetary boundaries, such as climate change, ocean acidification, and land-system change exist (Steffen et al. 2015). Extended transgression of planetary boundaries will put the Earth out of the relatively stable range (Holocene) that the Earth has been in for the last 11,700 years (Rockström et al. 2009, Steffen et al. 2015).

Application of the planetary boundary method to several industries, for example, the plastic or petrochemical industry have helped to understand which technological shifts and developments are required to align these industries with planetary boundaries (González-Garay et al. 2019, Bachmann et al. 2023). In this context, however, an assessment of the battery industry with the planetary boundary framework is missing. The present paper fills this gap by applying the planetary boundary framework to the battery industry. Using forecasts of technology mixes, production volume and recycling feedstock, we assess the absolute sustainability from a planetary boundary perspective in 2030, 2035 and 2040 for global battery production. We also analyse the impact of battery recycling and further process as well as technology innovations on the sustainability of the battery industry.

2 Background

2.1. Battery value-chain

Current research effort in the battery development is driven by several ambitions. Motivation comes from cost reductions and increased sustainability, as well as diversification by original equipment manufacturer and geopolitical strategies about access to material resources (Wesselkämper et al. 2024). From a technology perspective, batteries can be assigned to one of four broad technology categories, with different properties. The first group utilizes cathode active material (CAM) with lithium, manganese, cobalt, and a comparably low nickel content (low-Ni NMC). A similar yet different CAM with a higher share of nickel, represents the high-Ni NMC cluster. Increasing the nickel content enhances the specific capacity. Reducing the content of cobalt results in lower costs. Batteries with lithium-iron phosphate (LFP) do not use nickel or cobalt as part of the CAM. This lowers the energy density but also brings down costs and environmental impacts. Sodium-ion batteries (SIBs) can reduce the need for critical raw materials alongside lower costs and environmental impacts by replacing lithium with more abundant sodium (Usiskin et al. 2021, Zhang et al. 2024).

Recycling of battery waste is essential to reduce the amount of required virgin raw materials and reduce the risk of supply shortages for critical materials (e.g., Li, Ni, and Co) (Usiskin et al. 2021). Next to environmental benefits, recycling targets in core geographies contribute to a growing battery recycling industry (Neumann et al. 2022). State-of-the-art battery recycling employs pyrometallurgical or hydrometallurgical processes. In the pyrometallurgical process, a slag is

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produced via thermal processes from which materials are extracted (Neumann et al. 2022). In hydrometallurgical processes, batteries are mechanically shredded into a black mass, from which materials are recovered through leaching (Neumann et al. 2022). Material recovery rates of hydrometallurgy generally exceed those of pyrometallurgy (Mohr et al. 2020).

2.2. Production volumes and waste feedstocks

The forecast growth of the battery industry, including the shares of different technologies, is fundamental to the planetary boundary assessment. The ramp-up underlying this study projects a battery demand of 5.4 TWh per year by 2030 (Porsche Consulting GmbH 2023) (see **Fig. 1**) which fits well within the range of current market projections (International Energy Agency 2023, McKinsey & Company 2023). With high-Ni NMC and LFP likely leading the market by 2030, the share of SIBs will increase substantially from 2030 onwards (Degen et al. 2023, Porsche Consulting GmbH 2023).

The ramp-up of the battery industry results in high volumes of battery waste feedstock, consisting of production scrap, batteries from prototypes, test vehicles and end-of-life batteries. The waste feedstock is currently dominated by production scrap due to the high reject rate in the battery factories during ramp-up. Established Gigafactories are expected to reduce reject rates from 18% in ramp-up to 4% (Wesselkämper et al. 2024). From 2030, lower production scrap rates and the fact that batteries produced today will reach their end-of-life will increase the share of end-of-life batteries in the waste feedstock. In addition, the proportion of return batteries due to accidents or technical defects increases with growing BEV fleet.

3 Method

3.1. Planetary boundary framework

A central goal of the planetary boundary framework is to assess whether the Earth remains within its SOS for a set of planetary boundaries (Rockström et al. 2009). To date, no standard characterization model allows to transform life cycle inventory data gathered during an LCA into planetary boundary conditions. As a workaround, we use the individual characterization factors for each elementary flows provided in (Bachmann et al. 2023). Our analysis includes the two core boundaries climate change and biosphere integrity, which have been identified of having the potential to change the Earth ecosystem into a new state on its own if substantially and persistently transgressed (Steffen et al. 2015).

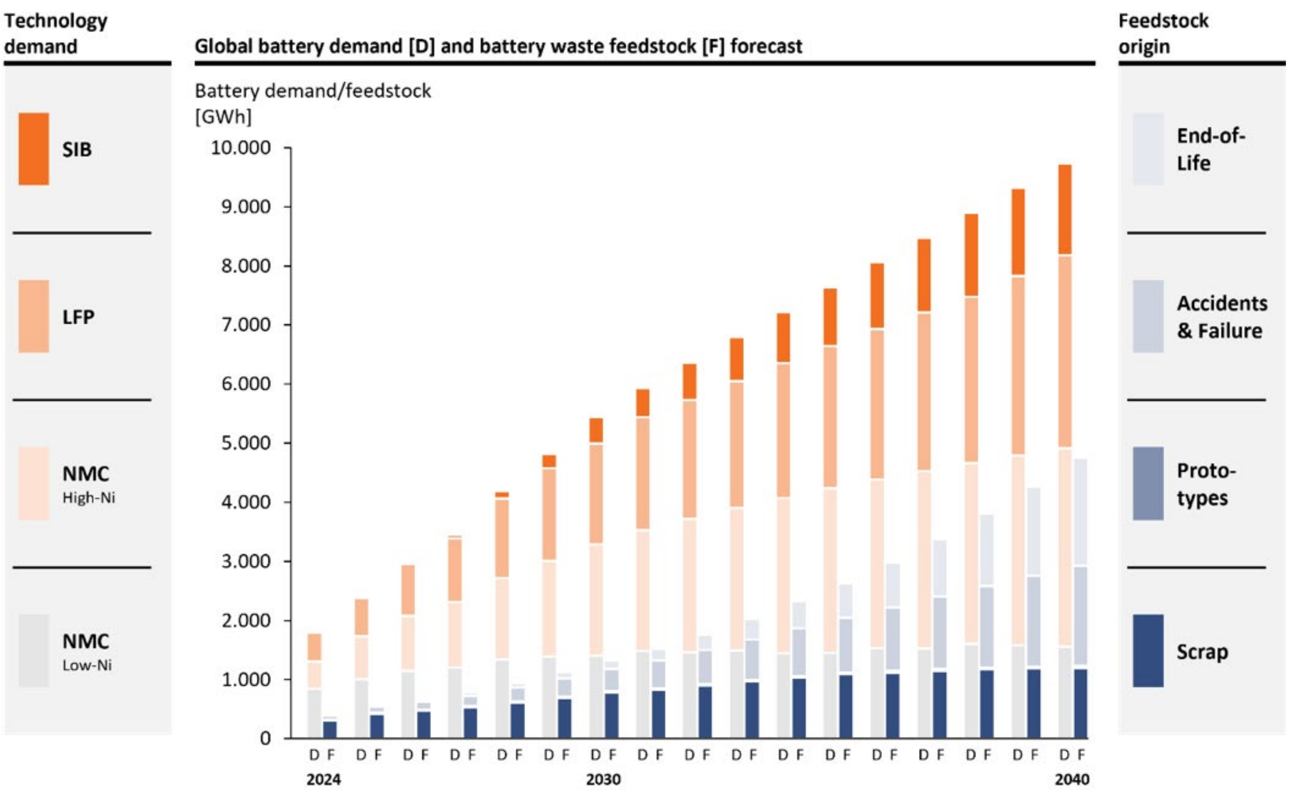

Fig. 1. Battery production and battery waste volume prognosis until 2040, split by battery technology cluster: NMC Low-Ni (NMC111), NMC Hi-Ni (NMC811), LFP and SIB.

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Additionally, we include ocean acidification, phosphorus cycle and stratospheric ozone depletion to our analysis, as these planetary boundaries are directly affected by the two core boundaries (Lade et al. 2020). Each boundary represents a crucial aspect of Earth's system, with potential irreversible consequences for both nature and humanity if transgressed (Steffen et al. 2015).

The present work scales down the share of SOS based on economic approach. Different approach exists to assign a part of the SOS to different activities within the global economy (Ryberg et al. 2018). One popular approach is an assessment based on economic metrics. For this, the total revenue of the battery industry is estimated and divided by global gross domestic product (GDP). For 2022 the global GDP of $100.8 trillion is taken from the World Bank Open Database (World Bank Open Data 2024). For the projection of the global GDP for 2030, 2035, and 2040 an annual growth rate of 2% is assumed. Revenue of the battery industry is calculated by multiplication of global production volumes (in GWh per year) and assumed average battery costs of $153 per kWh on system level.

3.2. Life cycle assessment

Life cycle inventory data for subsequent calculation of planetary boundary impacts is obtained following the ISO14040 standard for life cycle assessments (International Organization for Standardization 2006). Accordingly, we define the functional unit as the yearly global production and recycling of batteries for electric vehicles. Annual production and recycling volumes are estimated until 2040. While multiple production volume forecasts exist, this study is based on prior work from Porsche Consulting GmbH with a predicted production capacity of 5.4 TWh in 2030 (Porsche Consulting GmbH 2023), see **Fig. 1**. Waste flows consist of batteries which have reached end-of-life in the application or are rejected during production due to quality issues.

A cradle-to-grave system boundary is chosen (see **Fig. 2**). Consequently, raw material mining, product manufacturing, and end-of-life treatment are included. To assess the impact of recycling strategies, we assume that recycled materials are integrated in battery supply chain and used as a substitute for virgin materials.

Raw material mining comprises the extraction of materials (e.g. lithium, nickel, cobalt, copper, graphite and aluminium) including concentration and processing into battery grade materials. Ecoinvent 3.9 serves a background source for life cycle inventory data (Wernet et al. 2016).

Cathode and anode active material synthesis is modelled separately due to the comparably high energy demand of 27-31 kWh per kWhbattery (NMC), 4 kWh per kWhbattery (LFP) and 16 kWh per kWhbattery (SIB) (Wernet et al. 2016, Peters et al. 2021).

Cell manufacturing consists of three main parts which are electrode production, cell production and cell conditioning (Duffner et al. 2021). For the baseline scenario, state-of-the-art manufacturing processes (e.g., wet electrode production) have been set (Degen et al. 2023).

Cells that do not meet the quality requirements are discharged from the cell production line. Such waste cells might be fed into a recycling facility to recover valuable materials. Also, cells that have remained in use until their practical end-of-

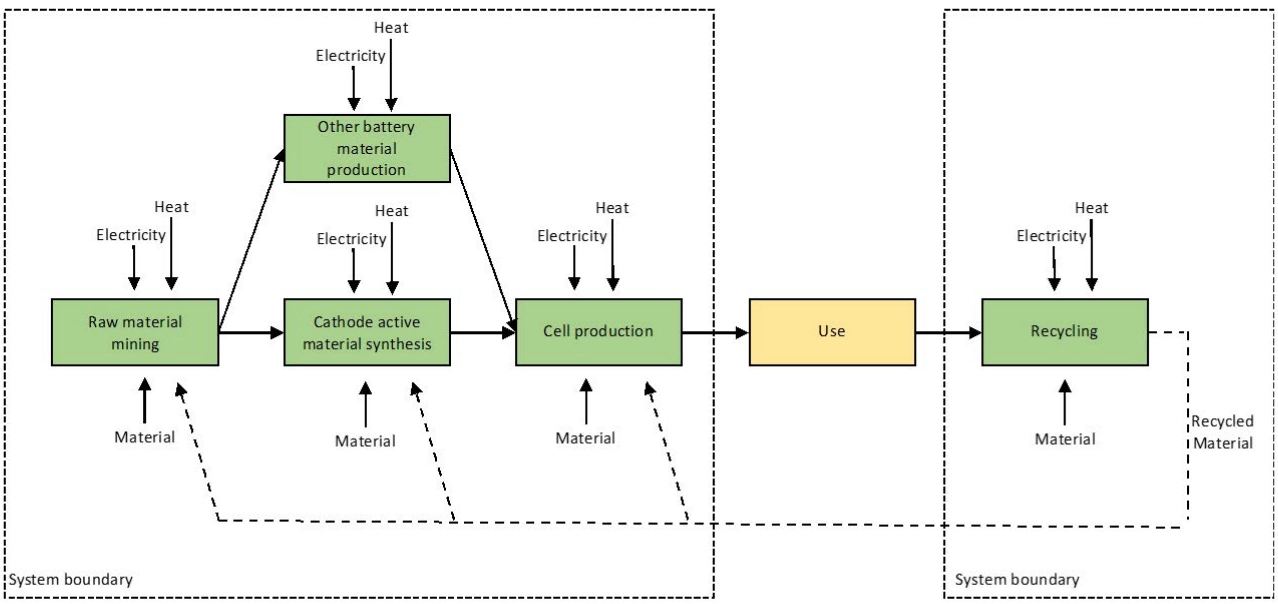

Fig. 2. System boundary of battery value-chain.

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life is reached can be fed into a recycling system. Life cycle inventory data and recovery rates for pyrometallurgical and hydrometallurgical recycling are adapted from (Gutsch and Leker 2024), see also supplementary information.

The focus of this work is on production and recycling of batteries, which battery manufacturer can influence. However, to put results into perspective, we also provide a schematic assessment of the use phase of batteries in vehicle application through a planetary boundary view. Doing so, we compare a BEV fleet of around 115 million vehicles in 2030 with the same number of ICEVs. Three different electricity mixes, based on IEA data, are modelled for battery charging. These are current electricity mix, stated policy mix, and sustainable electricity mix (IEA 2023, Richtie and Rosado 2024). An annual mileage of 15,000 km is used for the average vehicle.

3.3. Scenarios for technology improvement

To analyse the impact of technology innovations on the sustainability we conceive the following set of innovations which are either commonly discussed in the battery community (Harper et al. 2019, Duffner et al. 2021, Degen et al. 2023) (innovations 1-4) or resulting from the planetary boundary analysis (innovation 5):

1. Direct recycling process (for scrap and end-of-life batteries)
2. 100% renewable energy consumption (generated by onshore wind turbines)
3. Reduced energy consumption (data used from Degen et al. (Degen et al. 2023))
4. Direct lithium extraction (lithium sourcing through direct lithium extraction (Vera et al. 2023))
5. Reduced copper use (Reduction of 50% copper consumption)

4 Results

4.1. Planetary boundary results for status-quo battery industry

Fig. 3 shows the percentage of the SOS for each planetary boundary which is occupied by the battery industry in 2030. The SOS defines the limits of each planetary boundary within humankind can safely exists. In this context, the battery industry will occupy 7.6% of Earth´s SOS for climate change, a planetary boundary which is associated with increased extreme weather events and rise of the sea-level. Here, raw material production and energy intensive cell production are problematic. Also, by 2030 the battery industry will need around 2.3% of the SOS for ocean acidification and phosphorous cycle. Transgression of the SOS for ocean acidification implies a reduced pH level of the ocean, posing a threat to coral reefs and maritime food value chains (Rockström et al. 2009). Exceeding the SOS for phosphorous cycle is associated with groundwater contamination, algal blooms and risks for fresh water supply. While both raw material requirements and energy demand for cell manufacturing contribute to ocean acidification, the planetary boundary of the phosphorous cycle is essentially affected only by raw material consumption. For biosphere integrity, which addresses issues around diversity of species in the environment, the battery industry will occupy 0.7% of SOS. The contribution of battery production to stratospheric

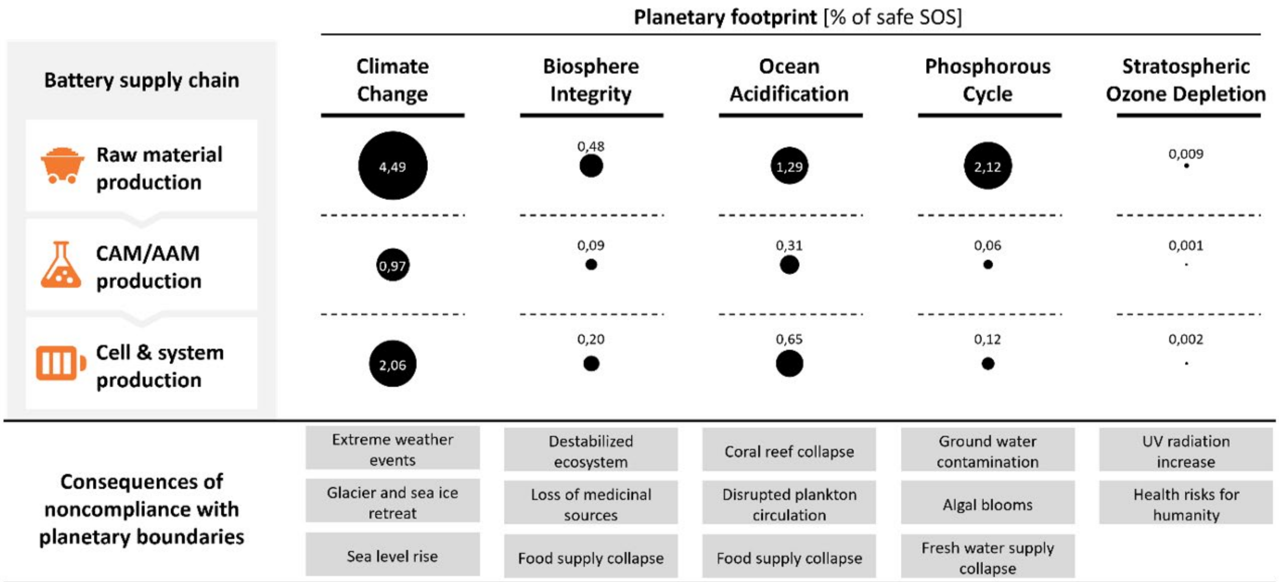

Fig. 3. The battery industries planetary footprint of total safe operating space in 2030.

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ozone depletion, which addresses the negative effect of a shrinking ozone layer on marine and land-based life, is comparably low (0.01%) (Rockström et al. 2009).

For each planetary boundary, the total of SOS should by assigned to different parts of the global economy (Ryberg et al. 2018). With an economic-based approach the total revenue of the battery industry is divided by global GDP. For 2030 we estimate the revenue of the battery industry as $830 billion. This represents 0.7% of global GDP in 2030. Consequently, following the approach of an economics-based assignment of SOS to different industries, the battery industry should be allowed to use 0.7% of the safe operating space ($SOS_{Battery}$).

Comparing the required part of the SOS with its assigned share, the battery industry clearly exceeds its planetary boundary targets for climate change, ocean acidification and phosphorous cycle, see **Fig. 4**. Our results suggest that remaining within $SOS_{Battery}$ is not problematic for stratospheric ozone depletion. For the planetary boundary of biosphere integrity, the assigned $SOS_{Battery}$ is in line with the requirement of the battery industry. The contribution of the battery industry to global GDP will further rise between 2030 and 2040, thus increasing the $SOS_{Battery}$. However, based on current trends, the battery industry will exceed its assigned $SOS_{Battery}$ even further. Although, due to optimization in battery technologies, the battery industry's share of the SOS will increase more slowly than production volumes until 2040, considerable efforts are still required to bring the rapidly growing battery in line with planetary boundaries.

4.2. Impact of recycling and changes in battery chemistry on planetary boundary results

So far, the analysis has not included any recycling of waste feedstock, thus representing a conservative approach. Recycling, however, will play a significant role in bringing the battery industry closer to its $SOS_{Battery}$. Based on the waste-feedstock, we calculate the potential benefit of recycling for planetary boundaries.

Recycling all incoming waste batteries in 2030 with pyrometallurgy can reduce the contribution to global SOS in climate change from 7.6% to 6.8% (see **Fig. 5**). With more efficient hydrometallurgy a reduction to 6.6% is possible. On the other side, 6.6% of global SOS still exceeds the GDP-assigned target of 0.7%. Thus, to reach SOSBattery for climate change the battery industry must reduce its footprint by an additional 79% beyond the 12% reduction achieved through hydrometallurgical recycling. For ocean acidification and phosphorous cycle, recycling reduces the required share of SOS, but it remains higher than the assigned $SOS_{Battery}$. A shift to low-nickel NMC batteries will increase the transgression of $SOS_{Battery}$. Using LFP batteries only would reduce the contribution to planetary boundaries due to fewer required critical raw materials. Despite disadvantages in energy density using SIBs would reduce the contribution to SOS substantially. In fact, for climate change, ocean acidification, and phosphorous cycle, a SIB-dominated battery industry would cut the transgression of $SOS_{Battery}$ by half. While practical implications, such as a lower

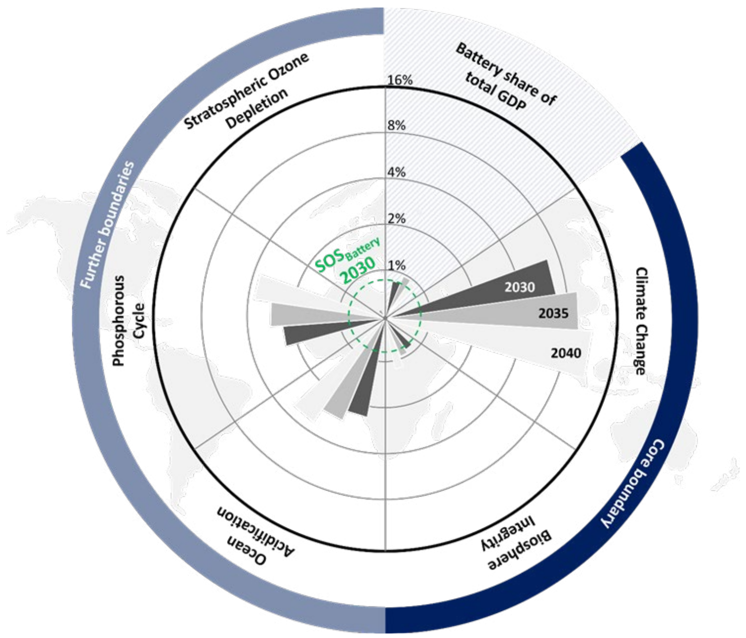

Fig. 4. The planetary and economic footprint of the battery industry in 2030, 2035 and 2040.

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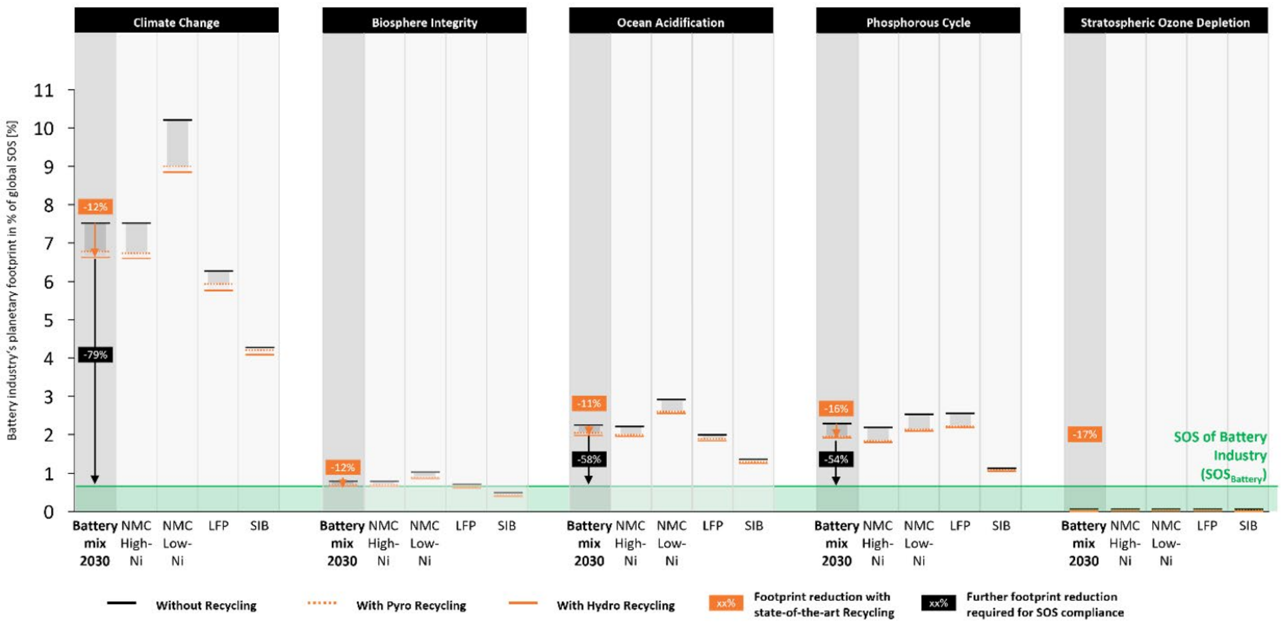

Fig. 5. Impact of battery recycling on planetary footprint of battery industry.

energy density, might limit the wide-spread adoption of SIBs in electric vehicles, results highlight that stra-tegic decisions about the market share of different battery technologies have a high impact on its absolute sustainability.

4.3. Scenario analysis

Further measures are required to bridge the gap between the current path of the battery industry and its $SOS_{Battery}$. Therefore, the impact of technological improvements to both cell manufacturing and recycling are assessed. Assessed innovations within the battery supply chain include direct recycling, direct lithium extraction, increased production energy efficiency, or a switch to 100% renewable energy. With use of copper accounting for more than half of phosphorous cycle impacts for NMC and LFP batteries, another innovation with reduced use of copper is also assessed.

Direct recycling produces CAM directly from spent batteries rather than extracting individual metals. By avoiding the complex separation and subsequent reprocessing of materials into CAM, direct recycling could be a promising alternative to state-of-the-art processes. **Fig. 6** shows that applying direct recycling instead of hydrometallurgy reduces the impact to all planetary boundaries.

The primary extraction of the critical raw material lithium, which occurs in hard rock ores or brines, is associated with considerable environmental impact. Lithium production from brines, which accounts for most of total lithium production, consists of an evaporation process in ponds, consuming a considerable amount of groundwater (Schenker et al. 2022). DLE is a more environmentally friendly method of extracting lithium by pumping concentrated brine to the surface, extracting the lithium and reinjecting the solution underground (Vera et al. 2023). A switch to DLE reduces impacts across all planetary boundaries by 3-4%, which is on par with the use of direct recycling.

Further process innovations such as dry coating, laser drying, and smart dry rooms have been of interest to research and industry. One recent study highlights that these new production technologies can lead to a 66% reduction in energy consumption during cell production (Degen et al. 2023). From a planetary boundary perspective, such measures bring significant improvements for the two core boundaries climate change (-16%) and biosphere integrity (-16%) as well as ocean acidification (-17%).

Next to reduced energy consumption, switching from fossil energy sources to renewable energy is generally seen as a promising way to enhance sustainability. Some battery cell manufacturers already promote the use of 100% renewable energy (The Economist 2023). Using renewable energy during active material synthesis and cell manufacturing brings large benefits for planetary boundaries. The contribution to ocean acidification can be reduced by 50%, allowing the battery industry to operate within the $SOS_{Battery}$ for this boundary. Additionally, this measure promises substantial reductions in climate change impact (-31%) and the phospho-rous cycle (-23%), helping the industry to approach the $SOS_{Battery}$. Reduced consumption of copper results in a focused benefit for the phosphorous cycle (-19%), without substantial benefits for other planetary boundaries.

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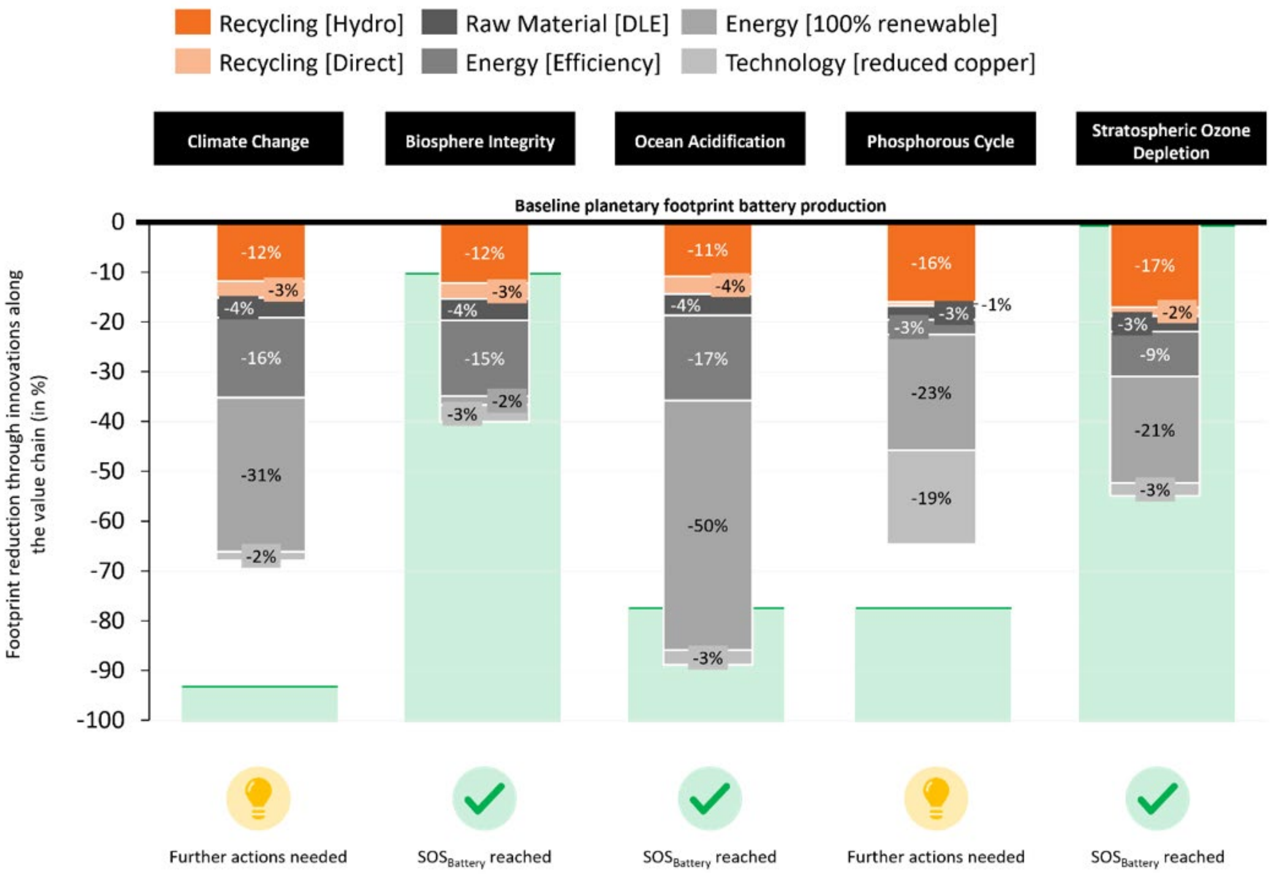

Fig. 6. Impact of future innovations to achieve $SOS_{Battery}$ in 2030.

Measures to reduce copper consumption could include a reduced thickness of the anode current collector foils or the implementation of alternative materials.

Overall, the innovations discussed show great potential for improving sustainability, but full implementation until 2030 is unlikely. For example, the speed of innovation in production processes, regardless of raw material production, recycling or battery production, is limited due to equipment lifetime. Also, a switch to 100% renewable energies is associated with major industrial and political efforts, as a solar park roughly the size of Cuba would be required to power the production of all batteries in 2030 with renewable energy.

4.4. Bringing the use-phase of batteries into perspective

Batteries enable the substitution of fossil-based energy by renewable energy in many applications and contribute to a more sustainable use of these application. The impact on the use phase must also be considered, when discussing batteries' sustainability. However, as battery manufacturers have no direct influence on the use phase, we assess the use of batteries separately from the battery production and recycling.

In the use-phase of batteries, electromobility plays the most significant role. To analyze the effect of the use of batteries from a planetary boundary perspective, **Fig. 7** compares the impact of the use phase of the projected BEV fleet in 2030 (ca. 115 million vehi-cles) with the identical number of internal combustion engine vehicles. The analysis shows that using only ICEVs in 2030 would account for 12% of the global SOS of the planetary boundary climate change. By switching to BEVs, the impact for all planetary boundaries can be significantly reduced. The electricity mix, which is used for charging the batteries has a major influence on absolute sustainability. In sum, electrification of the mobility sector combined with a sustainable electricity mix has potential to improve long-term compatibility with planetary boundaries.

5 Conclusion

The strong increase in demand for batteries has led to large industrial investments along the value chain. The major focus of research innovations in battery production and material development has been on increasing technical properties and reducing costs (Schmuch et al. 2018, Duffner et al. 2021). Recently, however, concerns about the sustainability of the

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fast-growing battery industry, especially due to the demand of critical raw materials, have come up. Across industries com-pliance with planetary boundaries has become an overarching challenge to avoid irreversible and problematic changes in the Earth's ecosystem (Rockström et al. 2009, Steffen et al. 2015, Lade et al. 2020). For the first time, the present analysis extends the planetary boundary framework assessment to the battery industry, bringing together an understanding of complex value chains, future technology innovations and sound environmental assessments.

On its current path, the battery industry will exceed its $SOS_{Battery}$ for several planetary boundaries. Without recycling, the production of batteries will exceed the planetary boundary for climate change by a factor of ten in 2030. A similar picture presents itself for ocean acidification and phosphorous cycle. Without sufficient measures, the production of batteries could, by 2040, occupy more than 10% of the global SOS for the planetary boundary of climate change, vastly exceeding its economic value as a share of global GDP. On a positive note, however, changes in battery technology, with an increased use of SIBs wherever possible, could reduce the transgression of planetary boundaries because less critical raw materials are required. Furthermore, consequent recycling of waste batteries brings the industry closer in line with its $SOS_{Battery}$.

Utilizing the planetary boundary approach to assess the absolute sustainability potential of technological innovations shows that improved energy efficiency in cell manufacturing, alongside the use of renewable energy, reduce the transgression of key planetary boundaries by a factor of two. Other assessed innovations, such as direct lithium extraction, bring modest benefits to all planetary boundaries, or high improvements to specific boundaries, such as reduced copper with ultra-thin collector processing, to phosphorous cycle.

Some limitations should be highlighted. First, based on methodological decisions and data availability, only five of the nine planetary boundaries have so far been included in the analysis. Second, uncertainty about the geographic location of battery production capacity led to an assessment of planetary boundaries on a global level, although the effect on some boundaries might better be captured on a detailed regional-level assessment. Future work should thus complement the present findings with a region-specific,

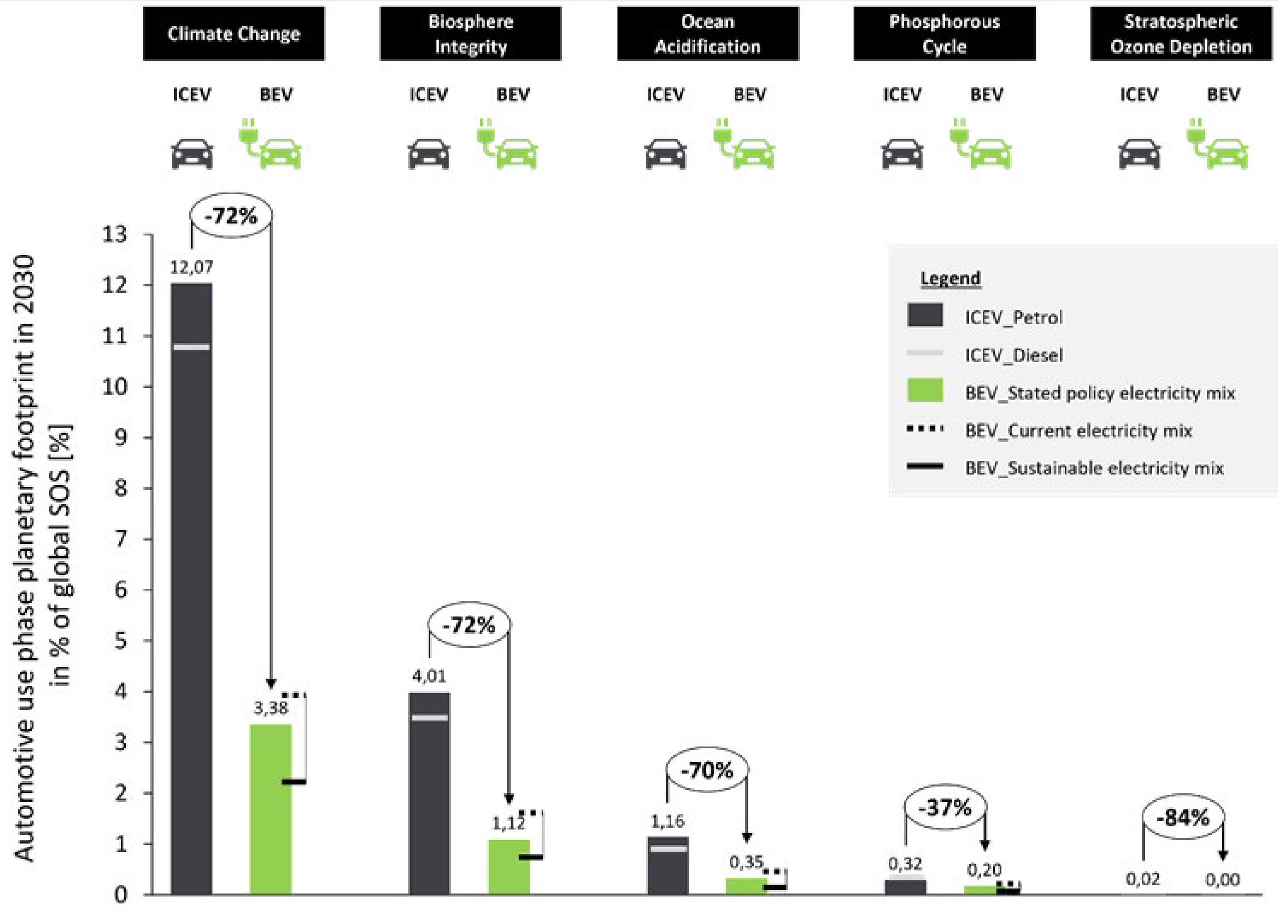

Fig. 7. Impact comparison of automotive use phase in 2030 for ICEVs and BEVs.

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rather than global focus. Third, the selected technology clusters for batteries somewhat simplify the diversity of used technologies, and some pathways, for example, a fast uptake of solid-state batteries are not explicitly considered.
Overall, this study shows that even if all innovations were fully implemented, the $SOS_{Battery}$ for climate change and phosphorous cycle would still be exceeded. Therefore, further measures and innovations are required. Although it will be difficult for the battery industry to remain within $SOS_{Battery}$ in all planetary boundaries, it should be recognized that the use of batteries in other industries such as the automotive industry brings benefits compared with the status-quo. In fact, if charged with high shares of renewable electricity, a global fleet of battery electric vehicles requires 2/3 less of the SOS during the use-phase than internal combustion engine vehicles would.
As governmental institutions have recognized the importance of adhering to planetary boundaries, carbon pricing mechanisms have been implemented in many regions. A price for CO_2 emissions monetarily incentivizes industries to reduce their footprint to stay within the core boundary of climate change. It has also been found that additional planetary boundaries, such as phosphorus cycle, biosphere integrity, and ocean acidification benefit from an increased carbon price (Engström et al. 2020). To avoid further price increases, industries should develop an intrinsic interest in complying with sustainability targets. Here, the planetary boundary framework should be used for an analysis about the possible benefit to overall sustainability of a particular innovation. A continuous monitoring of the rapid development and technological breakthroughs of the battery industry through a planetary boundary lens will support the frequent demand from policymakers and society for a more sustainable battery industry.

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CRediT authorship contribution statement

Niklas Kronemeyer: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Visualization, Writing – original draft. **Jens Leker**: Supervision, Validation. **Moritz Gutsch**: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Visualization, Writing – original draft.

Data availability

The authors declare that the data used as model inputs supporting the findings of this study are available within the paper and its Supplementary Information files. Additional questions about the data supporting the findings of this study can be directed to the corresponding author.

Declaration of competing interests

Niklas Kronemeyer is employee at Porsche Consulting GmbH. All other 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.

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