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LCA FOR ENERGY SYSTEMS AND FOOD PRODUCTS

Exploring future environmental impacts of Prussian white sodium-ion battery cells for stationary energy storage using prospective life cycle assessment

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Abstract

Purpose Sodium-ion batteries (SIBs) are a promising emerging rechargeable battery technology. This study explores future cradle-to-gate and cradle-to-grave life cycle environmental impacts of SIB cells used in a stationary battery energy storage system (BESS). The SIB cells contain the commercially viable Prussian white (PW) and hard carbon (HC) as electrode active materials. Their environmental performance is benchmarked against previous results for SIB and lithium-iron-phosphate (LFP) lithium-ion battery (LIB) cells.

Methods A prospective life cycle assessment (pLCA) is performed. Large-scale production and end-of-life treatment are modeled, and a cell production model specific to HC/PW SIB cells is developed by adjusting a LIB gigafactory model. Foreground system scenarios include different battery cell design choices, gigafactory electricity supply and end-of-life treatment options (incineration and direct recycling). A BESS is modeled in the use phase. Time-explicit inventory modeling of production, use, and end of life is applied. Different background system scenarios are applied, reflecting to different climate policies from the integrated assessment model REMIND.

Results and discussion Cradle-to-gate results show that improvements in gravimetric energy density and a low-carbon electricity supply to the gigafactory together reduces the environmental impacts considerably. The HC/PW SIB-specific cell production requires less energy (-20%) as compared to a generic SIB cell production. Cradle-to-grave impacts are sensitive to the number of battery cell replacements during BESS operation. Direct recycling can reduce impacts considerably for most impact categories by reducing the need for primary materials. Time-explicit inventory modeling reduces impacts for some impact categories compared to a non-time-explicit modeling. Benchmarking shows that HC/PW SIBs are environmentally competitive compared to other SIB and LFP LIB cells, and even notably better if certain measures, such as increasing the technical performance of the battery cell, are implemented.

Conclusion and recommendations The results show that cradle-to-gate and cradle-to-grave impacts can be considerably reduced. We recommend SIB cell developers and producers to prioritize increasing the technical performance of the battery cell (gravimetric energy density and cycle life) and supplying the gigafactory with low-carbon electricity, since these factors together have the largest influence on the results. Furthermore, time-explicit inventory modeling of production, use, and end of life has a notable effect on the results. We therefore recommend pLCA practitioners to apply such modeling, especially for long-lived products.

Keywords Sodium-ion battery · Next-generation batteries · Battery energy storage system · Prospective life cycle assessment · Direct recycling · REMIND

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1 Introduction

Rechargeable batteries are important for replacing fossil fuels with renewable and environmentally benign energy (International Energy Agency, 2024a). The global demand for rechargeable batteries is predicted to increase to 3–6 TWh/yr in 2030 (Link et al. 2025), a 10-20-fold increase compared to 2021 levels (Degen et al. 2023). Although rechargeable batteries have a key role in the energy transition, new challenges could arise, including potential impacts on the environment during their production, use, and end of life (EoL). Therefore, it is important to assess the environmental performance of rechargeable batteries to reveal those impacts and guide design towards reduced impacts, or possibly towards alternative technologies with lower impacts. Today, lithium-ion batteries (LIBs) are the dominant rechargeable battery technology for electric vehicles and battery energy storage systems (BESS) (International Energy Agency, 2024a). However, due to challenges related to resource availability as well as social and geo-political issues (Chaudary 2025), other battery technologies are on the rise. One such technology is the sodium-ion battery (SIB), which has recently entered commercialization (Li et al. 2025).

SIBs have several promising characteristics. They can be made with almost exclusively abundant raw materials (Tapia-Ruiz et al. 2021). For example, Prussian white (PW) is a commercially viable cathode active material (CAM) made from abundant elements (Li et al. 2025). Hard carbon (HC) can be produced from bio-based sources and is the most common anode active material (AAM) for SIBs (Qi et al. 2025). SIBs can reach gravimetric energy densities on par with lithium-iron-phosphate (LFP)-based LIBs and are a drop-in technology to LIB cell production, enabling faster scale-up (Tapia-Ruiz et al. 2021). Some SIB electrodes can be made from water-based slurries instead of the more commonly used organic solvent for LIBs (Mogensen et al. 2024). This enables cell production without solvent recirculation and lowers energy demand for electrode drying, according to Knehr et al. (2024). Taken together, these characteristics make SIBs advantageous from a cost perspective (Li et al. 2025).

Several life cycle assessment (LCA) studies have been performed on SIBs. The majority has been cradle-to-gate studies for a variety of CAMs (Batuecas et al. 2024; Carvalho et al. 2022; Degen et al. 2025; Lai et al. 2023; Peters et al. 2016; Schneider et al. 2019; Voß et al. 2025; Wellings 2021; Wickerts et al. 2024; Zhang et al. 2024; Jasper et al. 2025). A few studies have covered the entire life cycle (Guo et al. 2023; Jasper et al. 2022; Peters et al. 2021), where only Peters et al. (2021) considered a HC/PW SIB cell. However, all cradle-to-grave studies model a current time horizon. Given the recent commercialization of SIBs (Li et al. 2025), there is still room for technology-specific and system-wide improvements, where the latter are not considered in those studies. Furthermore, SIBs are long-lived products that require energy for production and cause energy losses during BESS operation. Therefore, as the roll-out of renewables is accelerating globally (International Energy Agency, 2024b), SIB impacts might change over time. This is also not considered in the previous studies. There is thus a lack of prospective considerations in previous cradle-to-grave LCAs of SIBs.

To address this gap, the aim of this study is to assess the future environmental impacts of HC/PW SIB cells with processes (production, use in BESS, and EoL) modeled at different future times. The cell production model is developed specifically for HC/PW cells and is compared to a more generic cell production. Future technical developments are considered, as well as background system scenarios according to different climate policies. The processes contributing the most are identified, and ways to reduce impacts are proposed. The results are benchmarked against those for other SIB and LIB cells from previous studies. The intention is to guide SIB cell developers, producers, and recyclers towards environmentally sound decisions, as well as contribute to the scientific efforts of relevantly assessing the future environmental impacts of SIB cells.

2 Method

This study applies prospective LCA (pLCA) to evaluate future environmental impacts of an HC/PW SIB cell, both with a cradle-to-gate and cradle-to-grave system boundary (Fig. 1). The cradle-to-gate boundary is selected to enable benchmarking of the studied SIB cell to previous studies, as well as a comparison between cell production developed specifically for HC/PW SIB cells and a more generic SIB cell production. For this boundary, a functional unit (FU) of 1 kWh of theoretical storage capacity at cell level is applied. A cradle-to-grave boundary is also considered to assess the full life cycle impacts of the cell and to identify dominating life cycle phases. For this boundary, the use of the battery cells in a BESS is considered. For this boundary, a FU of 1 MWh of delivered electricity over the BESS lifetime is applied. An attributional modeling approach is applied, meaning that linear physical flows to and from the product system that are considered environmentally relevant are quantified in the inventory modeling (Yang 2019). A subdivision of foreground and background systems is done, where the foreground includes cell production, use phase and EoL. The remaining product system constitutes the background system. The product system represents a global average,

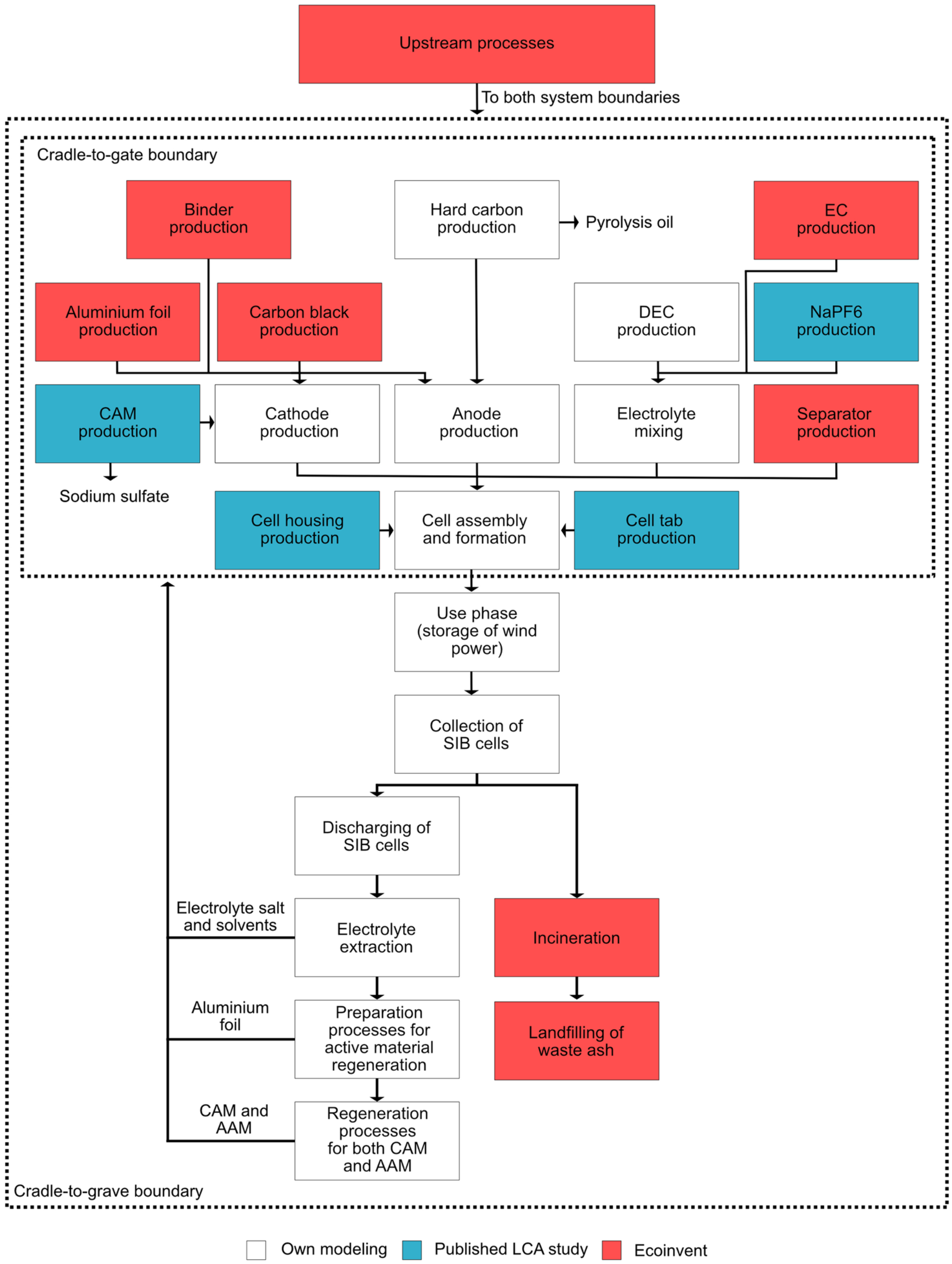

Fig. 1 Technical system boundaries. Colors indicate how unit process data are retrieved. AAM=anode active material, CAM=cathode active material, DEC=diethyl carbonate, EC=ethylene carbonate, NaPF6=sodium hexafluorophosphate, SIB=sodium-ion battery

meaning that global datasets are used if nothing else is stated. For multi-output processes, mass-based allocation is applied, since economic allocation in pLCA is challenged by uncertainties in future prices (Sander-Titgemeyer et al. 2023). The LCA modeling is performed using the Activity Browser software (version 2.11.1) (Steubing et al. 2020).

Although cells are assembled with other components to produce battery packs, modules, and installations, only the SIB cell is considered throughout the study. While it is also important to produce efficient and environmentally benign packs, modules, and installations, the SIB cell is the main novel and active constituent of such assembled products. Mature high-volume materials, such as steel pack materials, might otherwise dominate the impacts, providing little guidance to manufacturers of the more immature and still modifiable SIB cells.

2.1 SIB cell composition and materials

SIB cell materials are reported by a manufacturer of PW and HC/PW SIB cells (hereafter referred to as "the SIB manufacturer"). The anode and cathode both consist of current collectors coated with AAM (lignin-based HC) or CAM (PW), conductive additive (carbon black), and binders. The exact binder composition is confidential, but based on our previous work (Wickerts et al. 2024), we modeled a 50/50 mixture of carboxy-methyl cellulose and styrene-butadiene rubber. The binder acts as a glue between the active material, the conductive additive, and the current collector, where the last one also functions to provide mechanical strength and assist in heat removal during charge and discharge (Berg 2015). Both current collectors are made of aluminium, and the electrolyte consists of 1 M sodium hexafluorophosphate ($NaPF_6$) in diethyl carbonate (DEC) and ethylene carbonate. The separator is polyolefin-based. A multi-layer pouch of aluminium and plastics is modeled as cell housing. Table 1 shows the cell composition, weight, and cell performance parameters for two gravimetric energy densities, relevant for different scenarios (Sect. 2.3). Cell composition, weight and performance parameters with a gravimetric energy density of 150 Wh/kg are obtained from the SIB manufacturer. However, no information on the cell design was disclosed. A cell design computational model (CCM) (described in SI1), described by Chordia et al. (2025), is used to find a possible cell design (CCM outputs can be found in SI2). This design was later altered with the goal to improve the energy density further to 200 Wh/kg, assuming the same cell capacity, nominal voltage and electrode area (thus, that cell is lighter and thinner).

Table 1 Mass composition and weight of the studied SIB cells

Cell component (weight%)	150 Wh/kg cell*	200 Wh/kg cell
Cathode	41.1	48.5
Active material (PW)	35.0	44.3
Binder materials (CMC and SBR)	1.1	1.2
Conductive additive (carbon black)	1.4	1.6
Current collector (aluminium)	3.5	1.4
Anode	23.6	26.4
Active material (HC)	19.3	24.2
Binder materials (CMC and SBR)	0.3	0.3
Conductive material (carbon black)	0.4	0.4
Current collector (aluminium)	3.5	1.5
Separator (polyolefin)	5.0	5.6
Electrolyte (sodium hexafluorophosphate, DEC and ethylene carbonate)	27.4	16.4
Cell container	2.9	3.2
Pouch (plastic and aluminium)	2.6	2.8
Tabs (aluminium)	0.3	0.4
Cell weight (g)	~970	~690
Cell capacity (Ah)	47	47
Nominal voltage (V)	3.0	3.0

*A theoretical cell composition and not the one that the SIB cell manufacturer is producing

PW=Prussian white, HC=hard carbon, CMC=carboxy-methyl cellulose, SBR=styrene-butadiene rubber, DEC=diethyl carbonate

Production data for upstream battery cell materials is largely the same as in Wickerts et al. (2024), with the HC production modified to a higher yield in this study (40% instead of 20%). Also, production of DEC is instead modeled based on dimethyl carbonate transesterification with data obtained from Buitimea-Cerón et al. (2023). Cell material production data is either obtained for large-scale production directly or upscaled. Details are provided in Supplementary Information 1 (SI1).

2.2 Prospective inventory modeling

The prospective inventory modeling in this study attempts to represent the HC/PW cell's future life cycle, including gigafactory production developed specifically for HC/PW cells, processes occurring at different times, scenarios capturing potential technical improvements, and background scenarios covering different climate policies. SIB cells have recently entered commercialization, with multiple examples of large-scale production just started or planned (CATL, 2025; Maisch 2024; Murray 2024), but have not yet reached maturity. We estimate that SIB cells currently have a technology readiness level (TRL) of 7–9, a manufacturing readiness level (MRL) for production of 9–10, and an MRL for recycling of 2–4, based on, e.g., CATL (2025), Liu et al. (2025), and Faradion (n.d.). In this study, TRL=9 and MRL=10 are modeled for the whole life cycle, which seems possible to reach in 2030, or somewhat later for the recycling. This means that the processes in the life cycle need to be upscaled. Also, to account for potential future changes in SIB technology and recycling, foreground scenarios are constructed, as described in Sect. 2.3. The modeling of each life cycle stage in the foreground system is described in Sect. 2.4 (upscaled cell production), Sect. 2.5 (use phase), and Sect. 2.6 (upscaled EoL). All unit process tables can be found in SI2. The foreground system processes are modeled at specific future times and matched with background system datasets corresponding to those times. This approach is described in Sect. 2.7. Two background system scenarios are applied based on Ecoinvent version 3.10, as described in Sect. 2.8.

2.3 Foreground system scenarios

A *base scenario* and four additional what-if scenarios are constructed for the foreground system (Table 2). Scenario parameters are given approximate current performance values in the base case, and improved values in the other scenarios. In the base scenario, a gravimetric energy density of 150 Wh/kg at cell level is chosen based on information from the SIB manufacturer. This is in line with current reported gravimetric energy densities for SIB cells in other sources,

Table 2 Foreground scenarios considered in the study. EoL = end of life

Scenario parameter	Base scenario	Green gigafactory scenario	Technical performance scenario	Recycling scenario	Combined scenario
Gravimetric energy density, cell level (Wh/kg)	150	150	200	150	200
Cycle life (number)	2000	2000	6000	2000	6000
Electricity supply, gigafactory	Global average electricity mix	Low-carbon electricity mix (SE)	Global average electricity mix	Global average electricity mix	Low carbon electricity mix (SE)
EoL treatment	Incineration	Incineration	Incineration	Direct recycling	Direct recycling

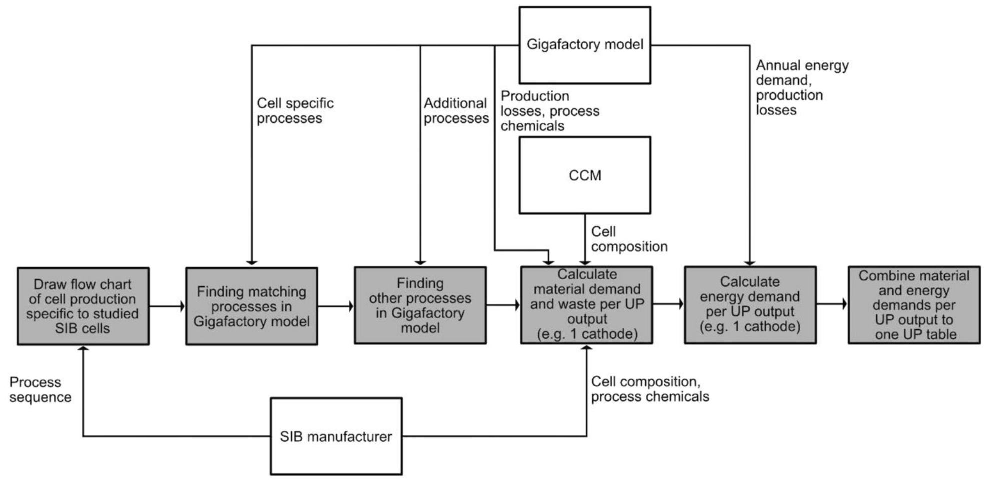

Fig. 2 Procedure for obtaining HC/PW SIB cell production unit processes. Grey boxes represent steps in the procedure whereas white boxes represent sources of data (models or the SIB manufacturer). CCM = cell design computation model, SIB = sodium-ion battery, UP = unit process

such as Stephan et al. (2023). A cycle life of 2000 cycles is applied in the same scenario, based on data reported by the BEPA (2024). The cycle life is “the number of charge and discharge cycles a cell can experience before the capacity fails to meet specific performance criteria” (Berg 2015), and is used to estimate the battery cell lifetime in this study. This scenario represents the conservative case of negligible performance improvements by SIB cell manufacturers over the time period 2030–2050. A global average electricity supply to the gigafactory is modeled. Incineration with landfilling of non-combustible components is assumed for the EoL in the base scenario. This is seen as a worst case still considered possible since SIB cells are mainly comprised of combustible materials.

The *green gigafactory (green) scenario* instead assumes a low-carbon electricity supply to the gigafactory. In the *technical performance (tech) scenario*, the gravimetric energy density at cell level and cycle life are increased to 200 Wh/kg and 6000 cycles, respectively (BEPA, 2024). This scenario represents the case of notable performance improvement by SIB cell manufacturers until 2030, so that no battery cell replacements are needed during the lifetime of the BESS installation (until 2050). A *recycling scenario* is considered, in which direct recycling is modeled instead of incineration. Direct recycling aims to regenerate electrode materials in a non-destructive way rather than breaking down the materials into chemicals (Xu et al. 2023). Finally, a *combined scenario*, combining all improvements, is considered. Note that the recycling scenario only influences the cradle-to-grave results.

2.4 Prospective cell production modeling

A gigafactory is modeled for the HC/PW SIB cell production, as the SIB cell production in 2030 is projected to be at GWh scale (Degen et al. 2023). As there is no inventory data for SIB gigafactories available, we modify a gigafactory model developed for nickel-manganese-cobalt (NMC) LIB cells (Chordia et al. 2025), adjusting it to represent HC/PW SIB cell production. To achieve such an adjusted cell production, data are needed regarding: (i) cell materials and composition, (ii) production process sequence, (iii) process chemicals, and (vi) how to scale factory level energy requirements to cell level. Two models are adopted to derive this adjusted cell production: the gigafactory model mentioned above and the CCM. The gigafactory model, obtained from Chordia et al. (2025), provides annual energy requirements on factory level, production losses, and process chemical amounts. The CCM provides the cell composition for the 200 Wh/kg cell. Detailed descriptions of these models are provided in SI1.

To construct unit processes corresponding to an HC/PW SIB-based gigafactory, the procedure in Fig. 2 is followed. First, a flow chart showing the process sequence for cell production is drawn, based on information from the SIB manufacturer. The process sequence, consisting of several subprocesses, can be found in SI1. This sequence differs from a generic SIB cell production (equal to typical LIB cell production as described in, e.g., Chordia et al. (2025) and Knehr et al. (2024). Second, the flow chart is used to identify cell-specific processes in the LIB gigafactory model. Third, additional processes required to operate a gigafactory are added (e.g., water treatment), which are found in the same gigafactory model. Fourth, material requirements and waste amounts are calculated per cell production subprocess and scaled to the unit process output. Material requirements are adjusted to include production losses obtained from the gigafactory model. Process chemicals are either obtained from the SIB manufacturer or the gigafactory model and scaled to the unit process output. Waste amounts are calculated from mass balances on a unit process level. Fifth, energy requirements are calculated using annual energy demands on factory level given by the gigafactory model and scaling them to a chosen unit process output. Details for this procedure can be found in SI1. Sixth, material and energy requirements are combined into one unit process.

For the generic SIB cell production, the energy demand for all subprocesses are obtained as-is (specific to NMC LIBs) from the gigafactory model. The total energy demand of such non-adjusted cell production is compared to the adjusted HC/PW SIB cell production.

2.5 Prospective use phase modeling

Produced SIB cells are modeled to be used for a BESS that integrates wind power to the grid. A 20 MW (100 MWh) installation is considered, which is suitable for integration of renewable electricity to the grid (Zhang et al. 2021). In this installation, battery cells are assumed to be cycled 300 times per year, accounting for weather limitations and varying storage demand, in line with the renewable energy integration modeled in Weber et al. (2018). Due to the battery cell focus in this study, only battery cell replacements during BESS operation and electricity losses occurring inside the cell are considered. The installation is assumed to operate for 20 years. Considering the different cycle life spans (Table 2), three battery cell replacements are needed for scenarios with 2000 cycles. For scenarios with 6000 cycles, no replacements are required. Electricity losses occurring during the use phase due to the less-than 100% efficiency of the cell are modeled as wind power produced in 2040, the average year of the installation's lifetime. A detailed description of the use phase modeling is found in SI1. An even more detailed, location-specific use phase modeling would involve parameters such as load curves, specific C-rates, and temperature (Peters 2023), which is out of scope considering the global perspective of this study.

2.6 Prospective end-of-life modeling

It is assumed that 100% of the depleted cells are collected and sent to either incineration or direct recycling, the latter assumed to exist at large scale from 2037 when the first SIB cells have reached their EoL. Incineration means that all combustible cell components are lost (Lombardo 2020), followed by landfilling of non-combustible components. Each cell component is matched with a suitable Ecoinvent incineration process, with energy recovery included if it is included in the process. A detailed process description is found in SI1.

Direct recycling is modeled in six main steps: Discharging, electrolyte extraction, disassembly, preparing electrodes for delamination, delamination, and electrode material regeneration. The electrolyte is extracted by supercritical or liquid carbon dioxide (Grützke et al. 2015). Delamination is when the electrode material is separated from the current collector (Xu et al. 2023). A novel delamination technique called "ice stripping" is modeled in this study, in which electrodes are sprayed with water and placed on a subzero surface (Chen et al. 2025). After a few seconds, the current collector can be peeled off from the electrode material. The current collectors are assumed to be regained after this step. The isolated electrode materials can now undergo regeneration to yield restored AAMs and CAMs with regained electrochemical performance. HC can be restored by vacuum drying and heat treatment, whereas PW is regained by a multi-step process, including resodiation (Chen et al. 2025; Shen et al. 2023). It is assumed that recovered HC, PW, electrolyte constituents, and current collectors have the same quality as their primary counterparts. For upscaling of the direct recycling (and the production of some battery materials), we apply the eight-step procedure in Wickerts et al. (2024). One step in that procedure requires calculation of energy requirements, for which the framework by Piccinno et al. (2016) is applied. A detailed description of the EoL treatments can be found in SI1.

Direct recycling implies a closed loop, in which recycled materials are used to produce new cells. For the cell materials that do undergo such direct recycling (CAM, AAM, current collectors and electrolyte), double crediting from also having an upstream recycled content needs to be avoided (Nordelöf et al. 2019). Therefore, inputs of these materials are modeled as effectively primary materials (apart from the shares coming from the direct recycling). To be consistent with the direct recycling scenarios, materials that undergo direct recycling are 100% primary also in the incineration scenarios. For the cell materials that do not undergo direct recycling (cell pouch, outside tabs, binders, additives, and separator), these are assumed to be recycled in an open loop and therefore modeled with the cutoff approach.

2.7 Time-explicit inventory modeling

We apply a time-explicit inventory modeling in this study by considering temporal positioning of the life cycle phases (Fig. 3). Battery cells with a cycle life of 2000 cycles are assumed to operate in the BESS for seven years, because of the 300 cycles per year (2000/300≈7). As a BESS lifetime of 20 years is assumed, the cells are sent to EoL treatment and replaced every seventh year (the last batch of cells are sent to EoL treatment without replacement after six years due to the assumed installation lifetime). Thus, for the scenarios with 2000 cycles, the cells are produced in 2030, 2037, and 2044. For scenarios assuming a cycle life of 6000 cycles, the cells are produced in 2030 and sent to EoL treatment in 2050, with no replacements needed.

The timing of the foreground system is matched with a corresponding timing of the background system, so that processes occurring in 2037 are connected to a background system representing the same year. The year in which primary materials are replaced by secondary materials from the direct recycling must be specified, since the replaced primary materials have different impacts at different times. We choose to perform the replacement in the respective EoL year. For the recycling scenario, replacement is done in 2037 for the first batch of battery cells, in 2044 for the second batch, and lastly in 2050 for the third batch of cells. For the combined scenario, all replacement is done in 2050.

The time-explicit inventory modeling is compared to a non-time-explicit modeling, where all life cycle phases occur in 2030. This comparison is only made for the base scenario and the cradle-to-grave boundary. Contrary to Müller et al. (2025), no time-explicit impact assessment is performed in this study.

2.8 Background system scenarios

Changes in the background system due to different climate policies are explored using the python-based tool Premise (Sacchi et al. 2022). Premise utilizes projections from integrated assessment models (IAMs) and match them to life cycle inventories (Ecoinvent 3.10 in this study), which produces prospective life cycle inventories under different climate policies and years. The IAM called REMIND is chosen for this study due to its focus on the energy system and since it appears to be in line with the current rapid growth of solar and wind energy (International Energy Agency, 2024b). Two REMIND scenarios are selected, one with countries implementing their national determined contributions resulting in a global mean surface temperature (GMST) of ~2.5 °C in 2100 (hereafter referred to as the 2.5 °C scenario), and one where strict climate polices are standard globally, leading to a GMST of ~1.5 °C in 2100

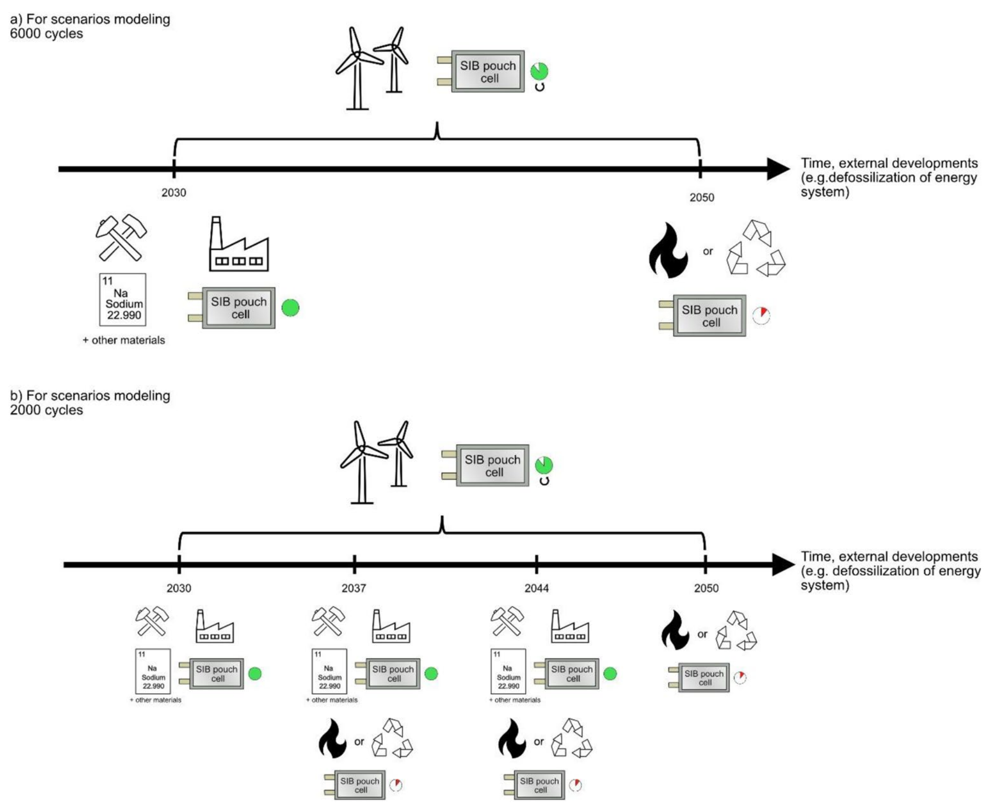

Fig. 3 Time-explicit prospective inventory modeling for (**a**) scenarios with 6000 cycles and (**b**) scenarios with 2000 cycles. Some icons in the figure are modified from Wickerts et al. (2024)

(hereafter referred to as the 1.5 °C scenario) (Sacchi et al. 2023). These GMSTs could be achieved through different socio-economic trajectories, which are captured by different shared socioeconomical pathways (SSPs) in REMIND (Riahi et al. 2017). For this study, the SSP2 narrative is chosen, in which the future unfolds in line with past historical developments. All REMIND scenarios used to produce prospective life cycle inventories are found in Table 3.

2.9 Life cycle impact assessment

Three impact categories are considered extra relevant for this study, of which one is assessed by two impact indicators. Climate change, assessed using IPCC 2021, is selected due to its global impact and urgency. Mineral resource scarcity is also considered highly relevant since one of the SIBs' potential benefits is the use of abundant materials, and it is of interest to assess whether that benefit is fulfilled in a life-cycle perspective. The mineral resource scarcity indicator in ReCiPe 2016 is applied, called the surplus ore potential (SOP), which considers the contribution of product systems to changing mineral resource quality (Berger et al. 2020). In Ecoinvent 3.10's implementation of ReCiPe, the characterization factor for cerium (and other rare earth elements, 3.19 kg Cu eq/kg) is incorrectly replaced with that for cesium (11,800 kg Cu eq/kg). This was discovered in this study since cerium initially became a hotspot, and has been corrected.

The SOP indicator is complemented with the crustal scarcity indicator (CSI) by Arvidsson et al. (2020), which considers the contribution of product systems to long-term mineral resource depletion. Thus, the two impact indicators capture different aspects of mineral resource scarcity (changing mineral grades vs. long-term depletion). Lastly, fossil resource scarcity is also considered relevant to reveal any fossil-related hotspots in the life cycle of the SIB cell. Some development efforts, such as the bio-based HC, are partly made to avoid fossil material inputs. Results for these three impact categories are provided in Sect. 3. The remaining impact categories from the ReCiPe package (Huijbregts et al. 2017) are also assessed and can be found in the SI1, but are not in focus in the main article.

3 Results and discussion

The results are presented and discussed for the cradle-to-gate and cradle-to-grave system boundaries in Sect. 3.1 and 3.2, respectively. Figure 4 shows cradle-to-gate impacts for the four scenarios, with process hotspots indicated. Figure 5 shows a comparison to previous SIB cell cradle-to-gate studies. Figure 6 shows cradle-to-grave impacts for the scenarios with hotspots indicated for life cycle phases. The effect of HC/PW-specific cell production is discussed in Sect. 3.1.1, and the implications of time-explicit inventory modeling are discussed in Sect. 3.2.1. Benchmarking vs. other battery cells is performed in Sect. 3.1.2. Cradle-to-gate impacts are, for the cradle-to-grave scope, referred to as "cell production". Most other impact categories in the ReCiPe package follow the same pattern as climate change and fossil resource scarcity, and are presented in SI1.

3.1 Cradle-to-gate results

Climate change and fossil resource scarcity co-vary strongly. In terms of foreground scenarios, the base and combined scenarios have the highest and lowest impact, respectively. For climate change, there is a reduction of about 50% between these two foreground scenarios, whereas for fossil resource scarcity, the reduction is just above 40%. The low-carbon electricity mix supplied to the gigafactory, modeled in the green scenario, and the higher specific energy, modeled in the tech scenario, yield roughly the same reduction under the 2.5 °C background scenario. When applying the 1.5 °C background scenario, the higher decarbonization of the energy system gives the tech scenario a slight benefit compared to the green scenario. This is due to a larger impact difference in the global electricity mix (supplied to all processes in the tech scenario) when switching from the 2.5 °C scenario to the 1.5 °C one compared to the same scenario switch for the low-carbon electricity mix (supplied to the gigafactory in the green scenario).

Process hotspots for climate change and fossil resource scarcity are the gigafactory, electrolyte production, and CAM production. The green scenario almost removes the gigafactory hotspot, whereas the tech scenario reduces the

Table 3 REMIND scenarios selected for the different life cycle phases and climate policies

Year	2030, 2037, 2044	2030–2050	2037, 2044, 2050
Life cycle phase	Cell production and upstream processes	Use phase	End of life
Background database, base climate policy	For 2030: REMIND 2030 SSP2-2.5 °C For 2037*: REMIND 2040 SSP2-2.5 °C For 2044*: REMIND 2040 SSP2-2.5 °C	REMIND 2040 SSP2-2.5°C**	For 2037*: REMIND 2040 SSP2-2.5 °C For 2044*: REMIND 2040 SSP2-2.5 °C For 2050: REMIND 2050 SSP2-2.5 °C
Background database, ambitious climate policy	For 2030: REMIND 2030 SSP2-1.5 °C For 2037*: REMIND 2040 SSP2-1.5 °C For 2044*: REMIND 2040 SSP2-1.5 °C	REMIND 2040 SSP2-1.5°C**	For 2037*: REMIND 2040 SSP2-1.5 °C For 2044*: REMIND 2040 SSP2-1.5 °C For 2050: REMIND 2050 SSP2-1.5 °C

*Only applicable for scenarios modeling 2000 cycles

**Used for the whole time period

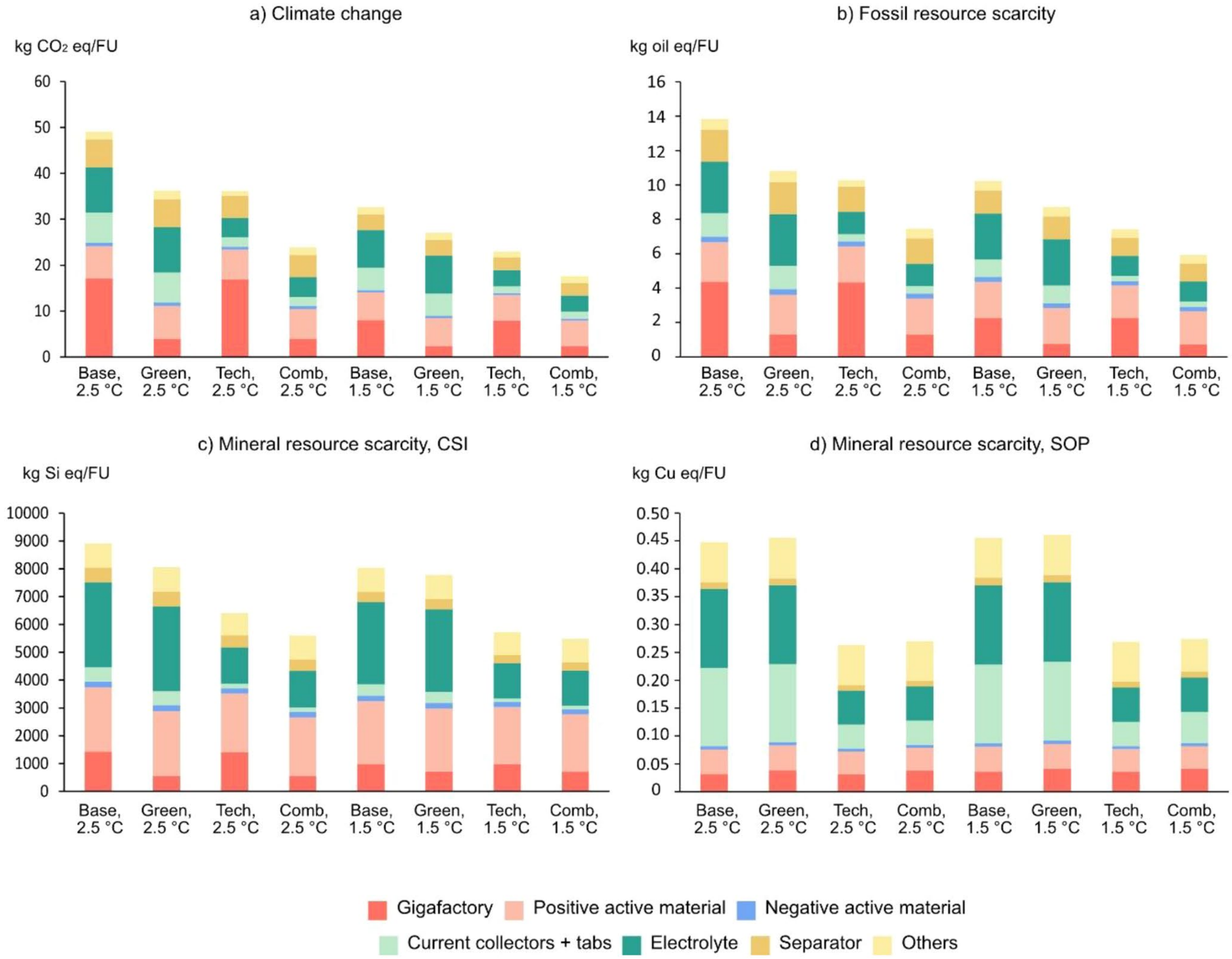

Fig. 4 Cradle-to-gate impacts for (**a**) climate change, (**b**) fossil resource scarcity, (**c**) mineral resource scarcity, CSI and (**d**) mineral resource scarcity, SOP. Base=base scenario, Green=green gigafactory scenario, Tech=technical scenario, Comb=combined scenario, 2.5 °C=2.5 °C background scenario, 1.5 °C=1.5 °C background scenario, CSI=crustal scarcity indicator, SOP=surplus ore potential, FU=1 kWh theoretical storage capacity at cell level

influence of the electrolyte. Reduced importance of electrolyte production in the tech scenario is due to a lower amount of electrolyte needed (-60%) for the 200 Wh/kg cell. When implementing all changes of the green and tech scenarios in the combined scenario, CAM production becomes the main hotspot.

For the CSI, the base scenario performs the worst while the combined scenario yields the lowest impact (a reduction of 36% between the two scenarios). For the SOP, the only scenario parameter with a notable influence on the results is the increased specific energy in the tech scenario, which leads to a lower material requirement. This reduces the SOP by approximately 40% compared to the base and green scenarios.

The CSI hotspots consist mainly of the electrolyte and CAM production, whereas the electrolyte production as well as production of current collectors and tabs constitute the main contributors for the SOP. For both impact indicators, the electrolyte hotspot is related to $NaPF_6$ production, where fluorine is the most contributing element for the CSI. The fact that fluorine emerges as a CSI hotspot is due to the product system containing abundant elements for the most part. That said, fluorine is not scarce in relation to other elements, for example copper. While fluorine has a significant contribution to the SOP result as well, phosphorus is the largest contributor. Current collectors and tabs represent a large share in the SOP results, since aluminium has a relatively high characterization factor in that method.

Regarding background scenarios, there is a reduction in impacts when moving from the 2.5 °C to the 1.5 °C scenario (about 30% reduction for the base scenario for climate change and fossil resource scarcity, about 10% for the CSI). However, a decarbonized electricity mix does not lower SOP results, as can be seen by comparing the base and green

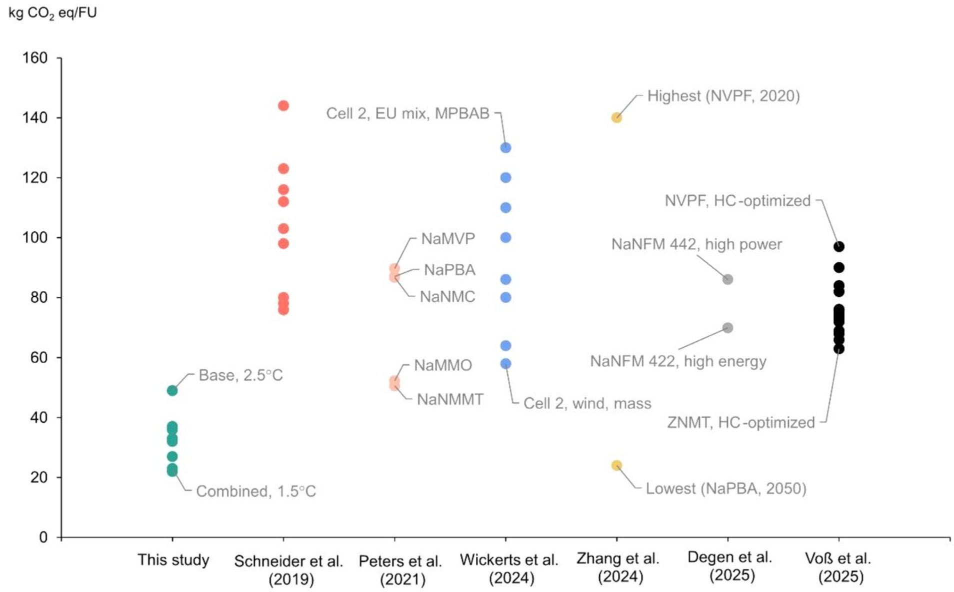

Fig. 5 Comparison of climate impacts of SIBs from this and previous studies. Highest and lowest results are highlighted. See Sect. 3.1.2 for an explanation of the scenarios considered and abbreviations used in the different studies

scenarios. For climate change and fossil resource scarcity, a reduction of impacts is expected as a more decarbonized background system yields lower climate change impact due to less usage of fossil fuels. The CSI results indicate that there is no burden-shifting from climate change to mineral resource scarcity when switching to a more decarbonized background system.

3.1.1 Influence of HC/PW-specific cell production

The non-adjusted gigafactory production modeled requires 77 kWh/FU for the 150 Wh/kg cell whereas the adjusted cell production needs 61 kWh/FU for the same cell. Thus, the adjusted cell production sequence reduces energy demand by approximately 20%, mainly by avoiding dry room for electrode processing (11%) and lower electricity requirement for cell formation (8.4%). At most, the lower energy use translates into impact reductions of 7–8% for climate change and fossil resource scarcity, 4% for CSI and 2% for SOP. The difference in energy use between adjusted and non-adjusted cell production highlights the importance of modifying gigafactory models to specific alternative cell chemistries. However, the adjustment mainly refers to an altered process sequence and therefore, additional adaptation to SIB-specific production would be beneficial. This includes potentially increased energy requirements for drying of PW-based SIBs to ensure enough water removal (see further SI1 Sect. S2.5.5).

3.1.2 Comparison to previous cradle-to-gate studies

For this comparison, six SIB cell LCAs modeling giga-scale production (explicitly or assumed by us) are included and compared regarding the three impact categories in focus. Schneider et al. (2019) report climate impact for a layered oxide SIB cell based on three scenarios with varying cell performance and discharge rates (C-rates: 0.25, 4 and 10). Peters et al. (2021) assess the climate impact of SIB cells with five CAMs: sodium NMC (NaNMC), sodium manganese vanadium phosphate (NaMVP), sodium manganese magnesium oxide (NaMMO), sodium nickel manganese magnesium titanium oxide (NaNMMT), and sodium Prussian blue analogue (NaPBA). In our previous work, we report results for climate change, fossil resource scarcity, and mineral resource scarcity for two different HC/PW SIB cells (called cell 1 and 2), for different energy mixes to the gigafactory (EU mix or wind power) and different allocation approaches (mass-based or main product bears all burden, MPBAB) (Wickerts et al. 2024). Voß et al. (2025) assess SIB cells with seven different CAMs at either basic or optimized HC performance, and report climate change impacts. The CAMs are NaNMMT, sodium nickel zinc manganese titanium oxide (ZNMT), sodium nickel iron manganese (NaNFM111), sodium vanadium phosphate iron (NaVPF), sodium vanadium pyrophosphate (NaNFPP), and NaPBA based on either iron or manganese. Degen et al. (2025) present a climate change and mineral resource scarcity of a layered oxide SIB cell (NaNFM) with either high energy or high power. Note, however, that their high SOP results might be due to the implementation error mentioned in Sect. 2.9. As the only published study utilizing the same background systems as in this study (REMIND 1.5 °C and 2.5 °C), Zhang et al. (2024) report climate change for different cell performances and three CAMs (NaNMMT, NaVPF, and NaPBA) from 2020 to 2050. The FU in all studies but Zhang et al. (2024) is 1 kWh of theoretical storage capacity

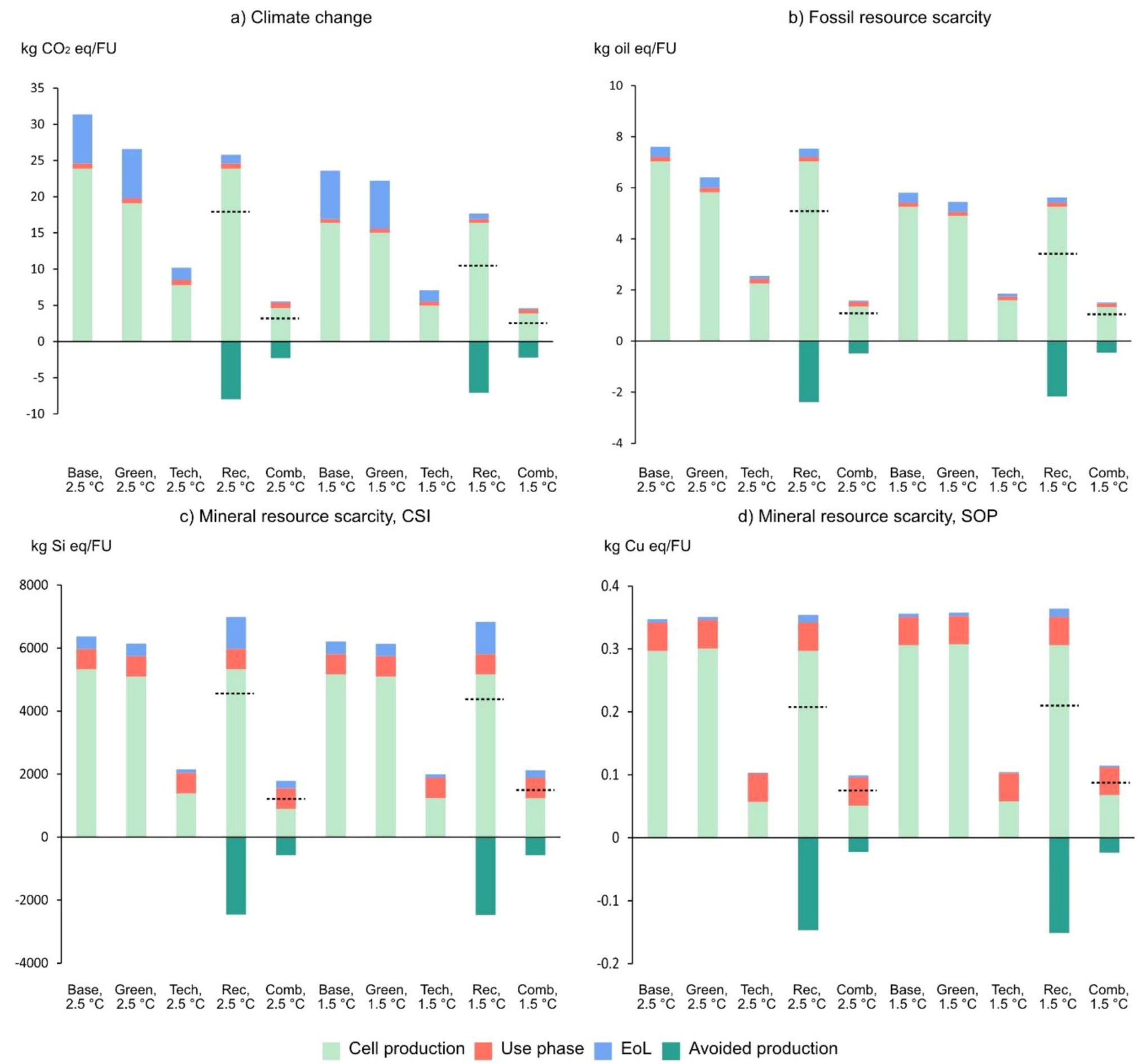

Fig. 6 Cradle-to-grave impacts for (**a**) climate change, (**b**) fossil resource scarcity, (**c**) mineral resource scarcity, CSI, and (**d**) mineral resource scarcity, SOP. Base=base scenario, Green=green gigafactory scenario, Tech=technical scenario, Comb=combined scenario, 2.5 °C=2.5 °C background scenario, 1.5 °C=1.5 °C background scenario, CSI=crustal scarcity indicator, SOP=surplus ore potential, FU=1 MWh delivered electricity over the installation's lifetime. Dashed lines represent the net impact

at cell level as in this study. For Zhang et al. (2024), we recalculated results into the FU of this study.

These studies consider different types of SIB cells, different cell performances, and other assumptions such as energy supply and allocations. That said, Fig. 5 indicates that the climate impacts from this study are low compared to most previous SIB cell results, probably in part due to the adapted gigafactory model and ambitious climate scenarios (≤2.5 °C). Regarding LIB cells, LFP are the most relevant to compare to since they have similar gravimetric energy densities as SIBs and can thus be used in similar applications. Examples of LFP cell LCAs indicate a climate change impact of about 50–80 kg CO_2-eq/kWh, again under different modeling and assumptions (Degen et al. 2025; Voß et al. 2025; Zhang et al. 2024). This indicates that the studied SIB cells can achieve lower climate impacts than LFP.

Regarding mineral resource scarcity, Degen et al. (2025) present a SOP result of 11–14 kg Cu-eq/kWh for the NaNFM SIB, and 19–22.2 kg Cu-eq/kWh for LFP cells. These results are notably higher than those of this study. However, these high SOP results might be due to the implementation error mentioned in Sect. 2.9.

3.2 Cradle-to-grave impacts

Implementing the combined scenario results in climate change and fossil resource scarcity reductions of over 80% compared to the base scenario. The longer cycle life modeled in the tech and combined scenarios result in the largest reduction. This is because the battery cells originally installed can be utilized for the whole service lifetime of the installation, without replacements. An almost as large reduction (>60%) is seen when implementing the technical scenario only. For the other scenarios, the battery cells need to be replaced three times during the installation's operating period, which leads to notably higher climate change and fossil resource scarcity impacts from cell production. Recovering cell materials via direct recycling reduces climate change and fossil resource scarcity results with about 30–40% in the 2.5 °C scenarios and about 40–50% in the 1.5 °C scenarios. The mineral resource scarcity indicators also demonstrate the importance of increasing cycle life. From the base to the combined scenario, impacts are reduced by about 80% for the CSI and over 70% for the SOP. Moreover, only direct recycling leads to CSI reductions of about 30% and SOP reductions of about 40%.

Cell production is the dominating life cycle stage for all impact categories. To lower these impacts, recommendations from the cradle-to-gate level are thus valid (Sect. 3.1).

Direct recycling reduces impacts compared to incineration for all impact categories. However, it might be difficult to reach such a high share of directly recycled materials per cell as modeled in this study, since the SIB market is expected to grow considerably, making the annual production of new SIBs much higher than the annual scrapping of old SIBs. Another aspect that could alter the benefit of direct recycling is disassembly, which might be challenging to implement efficiently at large scale (Lin et al. 2025). Therefore, automated disassembly techniques are needed, which require standardized cell formats (Wolf et al. 2024). The initial pretreatment and final regeneration steps of the direct recycling are partly modeled based on data from LIB recycling, specifically for lithium manganese oxide (Dunn et al., 2012) and NMC (Shen et al. 2023), which introduces uncertainty. These aspects should be further explored in subsequent studies to better understand the potential of direct recycling for SIBs.

Regarding background scenarios, the same reduction as on cradle-to-gate level is seen when moving from the 2.5 °C to the 1.5 °C scenario for climate change and fossil resource scarcity (about 30%). For the CSI and SOP, changes are negligible.

3.2.1 Implications of time-explicit inventory modeling

Compared to a time-explicit inventory modeling, the non-time-explicit inventory modeling yields about 25% higher climate and fossil resource scarcity results for the base 2.5 °C scenario. However, there is effectively no change for the mineral resource scarcity indicators. This is expected, since IAMs are developed to identify pathways to achieve climate targets and thus reductions in greenhouse gas emissions (and consequently fossil fuel usage). Another observation is the relation between the technical performance of the cell and the time-explicit inventory modeling. For scenarios with increased technical performance, all cells are produced in 2030. However, for scenarios with lower technical performance, there are several battery cell replacements which benefit from the less burdensome cell production beyond 2030. That said, the lower amount of material required for the high-performing cell still results in the lowest climate change and fossil resource scarcity.

As mentioned in Sect. 2.7, we have performed a partly time-explicit LCA by considering the timing of processes in the inventory modeling. However, technical processes might develop over time, resulting in impact reductions (Müller et al. 2025). This is an aspect that can be addressed in subsequent studies.

4 Conclusions

This study provides insights into the future life cycle impacts of HC/PW SIB cells that can be utilized by SIB manufacturers to reduce impacts. For the cradle-to-gate scope, the study shows that future impacts such as climate change and fossil resource scarcity can be reduced by more than half. The largest impact reduction is caused by combined foreground efforts, such as a low-carbon electricity supply to the gigafactory with a higher technical performance of the battery cell. For the cradle-to-grave scope, higher technical performance in terms of gravimetric energy density and cycle life is most important for impact reductions. Other improvements, such as the less energy demanding HC/PW-specific cell production and future decarbonization of energy supply in the background system, also contribute to impact reductions but to a lesser extent. These findings provide important information to SIB cell producers, developers and future recyclers as well as pLCA practitioners. Thus, for SIB cell manufacturers, we recommend prioritizing the development of high-performing HC/PW SIB cells with higher gravimetric energy density and longer cycle life, and sourcing of low-carbon electricity to the gigafactory. Compared to previous LCA results for SIB and LFP cells, the studied HC/PW SIB cells have comparatively low climate impact, particularly in the scenarios where the above-mentioned improvements have been implemented. For LCA practitioners, an important insight is that time-explicit inventory modeling can have a notable influence on the results, with a non-tome-explicit inventory modeling having about 25% higher climate change and fossil resource scarcity results compared to a time-explicit inventory modeling for the base 2.5 °C scenario. Therefore, we recommend LCA practitioners to consider time-explicit inventory modeling, especially for long-lived products.

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Data availability The data that supports the findings of this study is provided in the article and its supplementary information. Some data requires license to the Ecoinvent database for availability. Some information from the collaborating SIB manufacturer cannot be disclosed for confidentiality reasons.

Declarations

Conflict of interest The authors declare that they have no conflicts of interest.

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