Environmental life cycle assessment of emerging solid-state batteries: A review

Prasad Mandade [a,b,*], Marcel Weil [a,b], Manuel Baumann [a,b], Zhixuan Wei [c]

[a] *Helmholtz-Institute for Electrochemical Energy Storage (HIU), Ulm, Germany*
[b] *Institute for Technology Assessment and Systems Analysis (ITAS), Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany*
[c] *Institute of Physical Chemistry and Center for Materials Research, Justus-Liebig-University Giessen, Giessen 35392, Germany*

ARTICLE INFO

ABSTRACT

Energy storage systems are main drivers in various fields, especially in the context of energy and mobility transition. Battery technologies are one of those options offering good technical performance in multiple stationary and mobile applications. New batteries having potentially high energy density and higher safety with lower cost are in particular ideal candidates for mobility applications. At present especially, lithium-ion batteries are used, but they are facing challenges regarding sustainability and safety issues, which can be quantitatively analyzed with Life Cycle Assessments (LCA). New developments regarding various solid-state batteries (SSBs) are very promising to tackle these challenges, but only very few studies are available on the environmental assessment of SSBs. Prospective LCA methodology is used here to analyze the environmental hotspots over the different life cycle phases for emerging SSBs. This also helps in decisions making at an early stage of development. This review critically analyzes available LCA studies on SSBs focusing on the inventory data, scope of the assessment as well as the life cycle impact assessment results. An effort has been made to compare the different LCA studies considering global warming potential indicator. As a results, the analysis highlights difficulties in comparability due to inconsistencies associated with the data sources, goal and scope, system boundaries and the method of impact assessment etc. To facilitate a consistent comparison, a unification methodology has been proposed to compare different LCAs of SSBs. Overall, the proposed methodology will help to fill the knowledge gap between different existing LCA studies on emerging solid-state battery technologies and provides recommendations for future assessments.

1. Introduction

Concerns over the global environmental problems like climate change drive the energy and mobility transitions with the goal to address the major environmental problems related to energy storage. Especially batteries are considered as key technology for the energy and mobility transition. Over the last three decades, lithium-ion batteries (LIBs) with different chemistries are being used for many different types of applications such as portable consumer electronics, stationary storage systems and the mobility sector [1]. In recent years, the increased penetration of electric vehicles (EVs) in the transport sector created renewed interest new battery technologies as they represents a major component of the vehicle [2]. Lighter batteries with higher energy density could provide the vehicle with a longer range for mobility [3]. This pushes continuous research and development in battery technology

to provide safer and sustainable energy storage [4]. Typically, environmental impacts of transportation are closely tied to the use phase which is the source of fuel. As stored electricity in the batteries are the primary source of fuel for electric vehicles, efficient storage and use of electricity is the key to overall sustainable growth of the transportation sector [2].

Demand for batteries is expected to surpass 3.2 TWh over the next decade with the potential surge in electric vehicle (EV) batteries [5]. To accommodate this growth, cost-effective and environmentally friendly manufacturing methods are needed [6]. Increasing awareness of different stakeholders regarding the different sustainability aspects of supply chain strives to develop new battery technologies with lower environmental impacts. In this context, batteries powered by the Battery 500 consortium are aimed at providing 500 Wh kg^{-1} specific energy, but it will be hard with current LIB technology, which uses graphite anodes,

organic liquid electrolytes and transition metal oxide cathodes. Additionally, there is a limited potential for improving the performance of conventional LIBs further, since far reaching technological development has already been achieved with conventional cell chemistries on a cell level [7]. But on the battery pack level there are still opportunities for the improvement as demonstrated by Yang et al. (2021) for the LiFePO$_4$ batteries using optimized thermally modulated approach from cell to pack level [8]. Solid-state batteries (SSBs) could potentially change the outlook of the mobility sector. Several leading companies, including Toyota, BMW, Dyson, Honda, and others, have recently shown great interest in solid-state battery technology [9]. The development of solid-state batteries was pushed by concerns regarding safety and performance requirements for electric mobility. The solid-state battery is supposed to provide advantages in terms of safety, energy density and reliability. However, they suffer from some limitations such as the reduction in ionic conductivity of the solid electrolyte [10]. The recent development of emerging SSBs has created renewed interest over the last decade due to the advancement of solid-state electrolytes.

Different studies have been carried out to evaluate the environmental impacts of traction LIBs using various chemistries with different performance characteristics for mobility applications [3,11]. Supply risk associated with different raw materials like cobalt, nickel and other mineral materials along with lithium resulted in the advancement of batteries that contain earth-abundant elements as sodium or magnesium [12]. Economic Recycling posed new challenges for the success of the lithium batteries in the mobility sector [13]. All these aspects have been analyzed in recent studies as [14]. Surprisingly, not many studies are available on LCA of solid-state batteries in literature, which is major gap for the field. The absence of such studies makes comparative LCAs hardly possible as these analyses are very sensitive to aspects such as source of inventory data, impact assessment as well as the different goals and scopes of the assessment etc. However, the comparison of the environmental performance on a common basis is considered to help to find similarities and differences between different studies. Sometimes recompilation of the inventories of the existing studies are needed to make improvement in comparisons on a common functional basis [2].

This work aims to provide a in depth review of life cycle environmental impacts of SSBs, to identify potential hotspots and provide information for further requirements regarding environmental assessments and the implications for future possible design options. Additionally, a new unification methodology for comparative LCAs with a consistent basis is suggested. The article is organized as follows: Section 2 describes the current status of solid-state batteries with the focus on the solid electrolytes in comparison with existing batteries. Here, challenges and future opportunities for the SSBs are also discussed, including different solid electrolyte alternatives to provide a better understanding regarding sustainability as well as compatibility aspects; Section 3 describes the used review methodology for the existing LCAs on SSBs including the discussion of the different aspects of the life cycle stages; Section 4 discusses the discrepancies involved in existing LCA studies and also proposes the unification methodology for the comparative assessment between the different LCA studies to provide a common basis to support decision making. Finally, the last section summarizes the key conclusions of this work and discusses the future direction of the research.

2. Current status of solid-state batteries

The following section will provide relevant background information about solid state electrolyte-based batteries. First, the differences between conventional LIBs and emerging SSBs are discussed. This is followed by the description of different types of solid electrolytes and their properties, including inorganic, polymer and composite alternatives. The following part explains different solid electrolytes used in the development of solid-state batteries beyond lithium battery chemistries. The challenges associated with the production and functioning of solid-

state batteries are highlighted in the final summary.

2.1. Comparison of LIBs and SSBs

In principle, lithium-ion battery (LIBs) consists of two porous electrodes separated by a microporous separator with a liquid electrolyte that enables ion transport throughout the cell. Currently, commercialized LIBs employ intercalation-type cathode materials (such as lithium cobalt oxide) and graphite anode materials. Different LIB technologies are dominating a wide set of markets segments, but there are still several challenges regarding energy density and power density of batteries for future applications, such as electric vehicles (EVs). The development of lithium-ion batteries is driven by the rising demand for high energy density.

LIBs currently have volumetric and gravimetric energy densities up to 770 Wh/L and 260 Wh/kg. respectively for e.g., for lithium nickel manganese cobalt oxide (NMC): lithium-titanium-oxide (LTO) configuration 30–80 Wh/kg, and for lithium iron phosphate (LFP): graphite 60–160 Wh/kg while for lithium nickel manganese cobalt oxide (NMC)/ lithium cobalt aluminum oxides (NCA): graphite configuration energy densities are reported to be 140–260 Wh/kg [15]. According to Solid-State Battery Roadmap 2035+, Fraunhofer (2022) cell level gravimetric energy densities for emerging SSBs are estimated up to 350 to 500 Wh/kg with different solid electrolyte based SSBs [16].

However, high cost, toxicity and low availability of materials such as Co, Ni potentially restrict the large-scale use of some LIBs -types as NMC especially in the new electric vehicle [17]. At the same time, stability of the cells is directly related to the used electrolyte type as the continuous degradation of electrolyte during repetitive charge and discharge processes reduces the capacity and cycle life of the cell [18]. Lithium hexafluorophosphate (LiPF$_6$) dissolved in an organic solvent such as ethylene carbonate (EC) or ethyl methyl carbonate (EMC) is the most popular electrolyte for state-of-the-art LIBs. However, organic liquid electrolytes used in current LIBs pose major safety concerns regarding thermal instability. For example, operating the battery at 70 °C might cause solvent evaporation and cell rupture, resulting in the leakage of hazardous and flammable electrolyte [19]. Also, for batteries with lithium metal anodes, the uneven Li$^+$ deposition morphology on the Li metal will cause uneven current distribution, which eventually leads to a dendrite-like lithium growth. In the worst case, the lithium dendrite will penetrate the microporous separator and reach out to the cathode, which will circuit the battery and cause thermal runaway. The flammability of the organic liquid electrolyte will also add to the safety hazard in this circumstance [20,21].

New applications necessitate separate purpose-built batteries with new chemistries and architectures to suit varying performance and safety requirements [22]. To meet the intended safety standards, new, emerging batteries use a solid-state electrolyte with a significantly higher inherent stability. Such so called all-solid-state lithium batteries that use a solid electrolyte in place of a liquid electrolyte have been increasingly investigated recently [23,24]. Moreover, the enhanced safety of the solid-state batteries increases the feasibility of using lithium metal as anode, which, meanwhile, can increase the energy density of the battery system [25].

The fabrication approach for solid-state batteries largely depends on the mechanical properties of the solid electrolyte being used. Current approaches for solid-state batteries production are at low technology readiness levels and can hardly be scaled up to industrial scale as there are several problems to be solved. In addition, compared with organic liquid electrolytes, solid electrolytes generally exhibit lower ionic conductivity. Nevertheless, the potential of solid-state batteries is considered to be very high [26]. Constant research and development of solid electrolytes are ongoing to address these issues [10]. Schnell et al. (2018) explained the differences between current LIBs and SSBs production technologies with possible changes in the different production stages and challenges associated with them. In particular, this work

compared the production processes of a sulfide based all solid-state battery with a conventional lithium-ion battery and concluded that the processes for composite electrode fabrication can be adapted with some effort, while the fabrication of the solid electrolyte separator layer and the integration of a lithium metal anode will require completely new processes [27].

2.2. Solid electrolytes

The electrolyte is the most important SSB-component that drives the development of future batteries [28]. Research activities of newer and alternate electrolytes for all SSBs are driven by major incentives provided such as possible increment in energy density, specific power, and energy efficiency [29]. In all solid state lithium batteries (SSLB), solid electrolytes enable the use of lithium metal as the anode material instead of carbon/silicon regularly used in current LIBs, bringing about a 70% increment in volumetric energy density when compared to traditional anode materials [30,31]. At the same time they fulfill the dual role in SSBs as a ionic conductor facilitating transport of Li-ion and as a separator between electrodes [4]. The solid electrolyte's material qualities have a significant impact on the manufacturing technique for SSBs [32]. However, the selection of the appropriate solid electrolytes is difficult because numerous criteria must be considered, including conductivity, compatibility, stability, cost, environmental and electrochemical performance [33]. Solid electrolytes can be categorized into three major forms, namely inorganic, polymeric, and composite materials as displayed in Fig. 1.

2.2.1. Inorganic electrolytes

Inorganic electrolytes are non-flammable and contain no harmful substances, offering better thermal stability and conductivities than liquid electrolytes over a larger temperature range of -10 °C to 100 °C [24]. They can be classified into three types based on the anion chemistry including (i) oxide-based; (ii) sulfide-based and (iii) halide-based solid electrolytes. For the oxide-based electrolytes, several different crystal structures can be adapted, including perovskite structure (Li_{3x}-$La_{2/3-x}TiO_3$, LLTO), Natrium Super Ionic Conductors (NASICON)-type structure ($Li_{1.3}Al_{0.3}Ti_{1.7}(PO_4)_3$, LATP; $Li_{1.5}Al_{0.5}Ge_{1.5}(PO_4)_3$, LAGP) and garnet-type structure ($Li_7La_3Zr_2O_{12}$, LLZO). Generally, oxide-based materials demonstrate good ionic conductivity, superior oxidation stability and thermal stability. The NASICON-structured materials show

reduction stability due to the redox active Ti/Ge [35].

The ionic conductivity of the second category ii) sulfide-based electrolytes (amorphous and crystalline) is higher than that of oxide-based inorganic electrolytes but are chemically more unstable. Sulfides show an ionic conductivity between 2 and 27 mS cm^{-1} at room temperature (RT) (such as most widely studied $Li_{10}GePS_{12}$ and Li_6PS_5Cl), while oxides ionic conductivity varies between 0.25 and 1 mS cm^{-1}. Despite having advantages on ionic conductivity the sulfide based electrolytes suffer from lower thermodynamic stability [36]. At the same time, there are concerns regarding manufacturing difficulties and poor interfacial charge transport caused due to inferior contact with the electrodes limits the practical applications of inorganic solid electrolytes [22,37]. Oxide electrolytes generally exhibit high mechanical and chemical stability, but require high-temperature processing (sintering), are brittle and have a relatively poor ionic conductivity. Sulfide electrolytes are mechanically softer and more malleable than oxide solid electrolytes and easier to process (no sintering is necessary) [16]. iii) Halide solid electrolytes have also attracted increasing attention in recent years owing to their high oxidation stability and good compatibility with cathode composite materials. This intensive research interest can be dated back to 2018 when Panasonic revisited the Li_3YCl_6 and Li_3BrCl_6, which demonstrate good ionic conductivity of up to 1 mS cm^{-1} at RT. Thereafter, lithium halide compounds including chlorides and bromides with different central metal cations have been investigated, while their moisture sensitivity and anode instability remain as major challenges toward practical use. Among the current choices for solid electrolytes, inorganic (ceramic) materials have attracted much attention and are currently extensively explored for SSBs [38].

2.2.2. Polymer electrolytes

Polymer electrolytes are solid solutions of alkali metal salts in polymer matrixes which possess advantages over liquid electrolytes such as low flammability, lack of leakage, improved safety, and incomparable mechanical adaptability in low-temperature applications [39]. Polyethylene oxide (PEO) based complexes were used as solid polymeric ionic conductors by Fenton et al. (1973) and later extensive research has been carried out on polymer based electrolytes [40]. Zhang and Armand (2021) discussed on the development of solid polymer-based lithium metal batteries and highlighted the main achievements being made at both material and cell levels [41]. Castillo et al. (2022) summarized the recent progress on polymer-based solid-state Li-S batteries highlighting
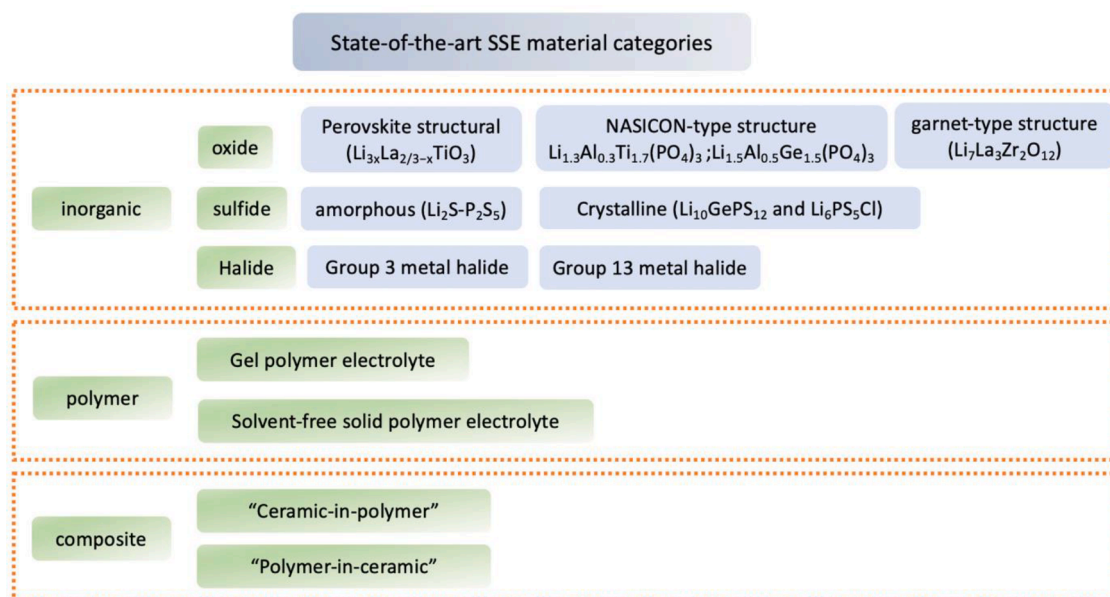

Fig. 1. Overview of different solid electrolyte types [32,34].

their mechanical stability and excellent flexibility. They also discussed the existing development and current challenges on polymer electrolyte-based solid-state batteries [42].

Polymer electrolytes show lower ionic conductivity at RT but can be enhanced with the addition of small numbers of ceramic particles that reduce crystallization with the improvement in ionic conductivity by enhancing the contact between the electrode and the electrolyte [43]. When compared to inorganic electrolytes, the polymer electrolyte's electrochemical window is lower (below 4 V) [17]. Organic polymer electrolytes provide several advantages over inorganic solid electrolytes, including increased flexibility, the capacity to make close electrode-electrolyte contact, and ease of processing.

Polymer electrolytes are categorized into two types, namely (i) gel polymer electrolyte and (ii) solvent-free solid polymer electrolytes. The first (i) gel polymer electrolyte has inferior mechanical qualities but a higher ionic conductivity, whereas the (ii) solid polymer electrolytes are mechanically stronger and may be made into free-standing electrolyte membranes without the use of additional mechanical supports [44]. Inclusion of the gel polymer electrolytes as a type of solid electrolyte has been the controversy in the scientific community but we included gel polymer electrolytes in the figure mentioning it as a subtype of the polymer electrolyte. Ionic conductivity of gel polymer electrolytes, incorporating organic solvents is as high as $\sim 10^{-3}$ S cm^{-1} at RT, while solid polymer electrolytes show poor ionic conductivity lower than 10^{-5} S cm^{-1}. Gel polymer electrolyte is mechanically stable, adaptable, and formed by immobilizing the liquid electrolyte in the polymer host matrix. This avoids the risks of leakage and solvent evaporation along with that it also provides beneficial characteristics of a polymer matrix with the superior ionic conductivity of liquid organic electrolytes by sharing both the diffusive and cohesive properties of solids and liquids accordingly. In addition to that, the encapsulation of a liquid electrolyte in a solid polymer host matrix results in an enhanced electrode/electrolyte contact and interface, especially with graphite anodes [45,46]. Polymer electrolytes are also classified as polyether based and other organic polymer electrolytes such as polycarbonate, polysiloxane and plastic based electrolytes [38]. Compared to both inorganic solid electrolytes and liquid ones, solid polymer electrolytes (SPEs) combine both good adaptability and higher safety, which makes them preferred for SSBs. Polymer electrolytes are the most established amongst all solid electrolytes in terms of material availability and production technologies. However, limited ionic conductivities at RT, poor chemical compatibility with high-potential cathode active material (CAM)and a low limiting current density due to the ionic conduction mechanism are challenges on the path to a broader market implementation [47].

2.2.3. Composite electrolytes

Composite or hybrid solid electrolytes are composed of an ion conducting organic polymer and an inorganic material (e.g. SiO$_2$, Li$_{1+x}$Al$_x$Ti$_{2-x}$(PO$_4$)$_3$) [32]. Composite electrolytes show the advantages of respective components by compensating drawbacks of the polymer and inorganic electrolytes and to enhance the overall performance of the solid electrolyte regarding mechanical properties, electrochemical window and transference number [48]. The typical ceramic/polymer composite solid state electrolyte (SSE), which combines polymer material to promote interfacial compatibility between electrodes/electrolyte and inorganic fillers to govern ion migration, provided a promising performance for composite electrolytes [49]. Potential advantages of the hybrid composite electrolytes with the distinctive merits of solid inorganic electrolytes (SIEs) and solid polymer electrolytes (SPEs) are becoming increasingly attractive and present great research potential in the field of SSB.

Composite electrolytes are classified into two types, namely polymer-in-ceramic and ceramic-in-polymer. This hybrid composites can be simply obtained by dispersing inorganic electrolyte particles in a polymer matrix. Hybrid solid state electrolytes (HSSEs) can be transformed based on the contents of polymer and inorganic in the composites, between "ceramic-in-polymer" and "polymer-in-ceramic". Such change in composition would notably alter the ionic transport behavior as well as the mechanical properties [50]. The polymer-in-ceramic interlayer shows high mechanical strength, hindering Li-dendrite propagation, and the thin ceramic-in-polymer outer layers provide smooth and flexible surfaces to the electrodes, ensuring excellent interfacial contact. The ionic conductivity of these electrolytes can approach $\sim 10^{-3}$ S cm^{-1} at RT from $\sim 10^{-4}$ S cm^{-1} for a polymer electrolyte with low-molecular-weight additive [51].

2.3. Potential solid electrolytes for different battery chemistries

As mentioned before, the potential of further optimization of liquid electrolyte-based batteries is diminishing and expected to reach limits in the coming decades. Therefore, the next generation solid electrolyte-based battery technologies are increasingly in focus and could reach the market in larger volumes in next years if named problems are resolved. Different battery chemistries play a significant part in the performance of the battery and its constituent elements have considerable environmental impact from a life cycle as well as resource scarcity point of view. To this end, other chemistries, in addition to Li-ion, are also being investigated for solid-state batteries [22]. For instance, Na and K are earth abundant elements which are considered to be promising candidates for "post-lithium" energy storage devices. More importantly, as alkali metal elements, both of them share the similar working principle with lithium in terms of secondary batteries, which gives great feasibility to transfer the knowledge gained from LIBs to Na/K-ion batteries. On the other hand, Mg, Ca, Zn, and Al also attracted tremendous attention in recent years. Not only they are earth abundant elements, but their multi-valency also contributes to a higher volumetric energy density by increasing the number of electrons involved in the electrochemical process, which potentially can meet the increasing requirements of energy storage with high volumetric energy density batteries [23,31]. For example, Magnesium has approximately the double volumetric capacity of lithium. aluminum has the highest volumetric capacity (8040 mAh cm^{-3}), about four times that of lithium, as well as a high gravimetric capacity. However, presently the development of beyond-lithium battery technologies is still at their initial stage, and none of these are competitive with the Li based chemistries. LIBs have seen their energy density treble at the cell level, with battery pack costs falling from \$1100/kWh in 2010 to \$156/kWh in 2020. The following part introduces several successful cases of solid-state batteries with different chemistries.

Li et al. (2015) demonstrated the viability of using LiPON solid electrolyte in lithium batteries with a high-voltage cathode and a lithium metal anode [52]. Zhang et al.(2022) reported high-performance with good cycling stability of polyvinylidene fluoride (PVDF)-Li$_{6.75}$La$_3$Zr$_{1.75}$Ta$_{0.25}$O$_{12}$ (Ta-LLZO) composite polymer electrolyte with Li-LCO battery chemistry [53]. Han et al. (2018) showed excellent cycle stability and higher capability of LLZO electrolyte for Li-LCO battery with cathode-electrolyte interface modification by incorporation of Li$_{2.3}$C$_{0.7}$B$_{0.3}$O$_3$ solder with solid electrolyte [54]. Along with the named lithium-ion batteries Li-S and Li-air batteries also gained attention due to their higher energy densities. PEO polymeric electrolytes and inorganic sulfide glass electrolytes have been used in all solid-state batteries for the Li-S. Tao et al. (2017) reported a battery capacity of 900 mAh g^{-1} with a high cycle stability and coulombic efficiency for Li-S batteries utilizing a composite electrolyte of PEO/LLZO [55]. Liu et al. (2015) used LAGP electrolyte for Li-air batteries and showed high initial specific capacity of 2800 mAh g^{-1} with single-walled carbon nanotubes [56].

Sodium ion batteries are most promising alternative after lithium-ion batteries because sodium is the next targeted element after lithium considering its atomic weight, abundant availability, and standard potential. Dai et al. (2021) discussed different modification methods of solid electrolytes to improve the electrochemical performance for all-

solid-state sodium-ion batteries [17]. Hayashi et al. (2016) reviewed ion conductivities for Li$^+$ion and Na$^+$ ion for sulfide solid electrolytes. Ionic conductivities of solid electrolyte for sodium ion varies from 1.2×10^{-3} to 7.3×10^{-6} S cm^{-1} [57]. Yu et al. (2018) developed and used Na$_{11}$Sn$_2$PSe$_{12}$ electrolyte in a Na-Sn/TiS$_2$ all-solid-state battery cell and demonstrated excellent rate performance with a high reversible capacity of 66.2 mAh (g of TiS$_2$)$^{-1}$ after 100 cycles with cycling retention of 88.3% at a rate of 0.1 C at RT [58]. Deng et al. (2017) investigated electrochemical performance of layered Ca-doped Na$_2$ Zn$_{2-x}$ Ca$_x$TeO$_6$ (NZTO—C$_x$) electrolytes with the conductivity of 7.54×10^{-4} S cm^{-1} with improved cycle stability [59]. Hou et al. (2017) demonstrated a safe and durable all-solid-state sodium ion battery with Na$_{0.67}$Ni$_{0.23}$Mg$_{0.1}$Mn$_{0.67}$O$_2$ as the cathode, metallic sodium as the anode, and solid polymer electrolyte (SPE) film of perfluorinated sulfonic in the Na form (PFSA-Na) swollen with ethylene carbonate-propylene carbonate mixed solvents as the electrolyte [60]. Gandi et al. (2022) reviewed the development of glass ceramic cathode/solid electrolytes for all solid-state sodium ion batteries. These electrolytes are still in the development stage as several challenges have to be addressed to improve the cycle life of all solid state inorganic batteries (ASSIBs), along with the reduction of cost of production [61].

Ferrari et al. (2021) discussed solid state post-Li metal ion batteries including K, Ca, Mg, Na based batteries. This study also discusses different potential solid electrolytes for these batteries and suggested the further scope and potential of the battery technology development [38]. Yan et al. (2020) presented solid Mg^{2+} electrolytes based on ammine magnesium borohydride composites, Mg (BH$_4$)$_{2-x}$NH$_3$. The MgO nanoparticles showed a conductivity of the order of 10^{-5} S cm^{-1} at RT and increased up to 10^{-3} S cm^{-1} at a temperature of 70 °C representing important advancement of solid-state ion conductors for Mg^{2+} [62]. Lu et al. (2017) investigated the electrochemical performance of Li, Na, Ca, and Mg borohydrides for solid-state Li, Na, Mg, and Ca batteries [63]. Dong et al. (2021) discussed about potential enhanced electrochemical performance of the solid-state zinc-ion batteries (ZIBs) along with the future directions needed to guide research for its commercialization [64].

2.4. Challenges associated with the production and functioning of SSBs

Solid state battery technologies based on the different classes of solid electrolytes face various technological challenges such as the scale-up of material production, production of the different battery components and compatibilities between their performance aspects [4].

The interfaces between the different components of the battery are very critical in designing solid-state battery cells. The electrochemical stability window of an electrolyte indicates at what electric potential the electrolyte is reduced (anode) or oxidized (cathode). Sulfides have narrow electrochemical stability window, which limits the electrode active materials with which they can be readily combined. For solid polymer electrolytes, the combination with high-potential cathodes poses a challenge due to their low ionic conductivity, while their electrochemical stability window does not hinder combination with the anodes [18]. Wang et al. (2021) discussed interfacial challenges associated with sulfide electrolytes for SSBs despite having benefits of higher conductivities [65]. Besides electrochemical compatibility, the chemical stability of the electrolyte material is a challenge that needs to be addressed. Coatings of the cathode active material can prevent decomposition reactions of sulfides at the interfaces. Oxide electrolytes have exceptional electrochemical and chemical stability. Processability challenges must be addressed for the electrolytes for e.g., oxides electrolytes have to be sintered with cathode, but it is harmful to the active materials due to high temperature involved in the sintering process [23]. Sulfide electrolytes show instability towards the polar solvents and must be processed with non-polar solvents. Conventional binders such as polyvinylidene fluoride (PVDF) and carboxymethyl cellulose (CMC) show poor solubility in nonpolar solvents hence other binders such as styrene – butadiene rubber and silicon rubber have to be used to ensure the mechanical stability, but the addition of binders also reduces the ionic conductivity of the electrolyte. SSBs with solid electrolytes suffer from mechanical instability, this issue has to be addressed by finding the balance between material and processing technique at the level of production stage of the cell [3]. Overall, SSBs are still at low technology readiness level (TRL) stages and face several challenges according to a report of the European commission on solid-state-lithium-ion-batteries for electric vehicles. Polymer based SSBs are considered to be at a Technology Readiness Level (TRL) 7–8 while inorganic and hybrid solid electrolyte based SSBs are still at basic research of TRL 4–6 level [66]. But among the potential solid-state batteries, only polymer based SSB are available on markets with an annual production capacity of less than 2 GWh with a primary application target on electric buses. The biggest drawback of the current generation of polymer SSB is the operating temperature of 50–80 °C. Any SSB technology entering the market is expected to start at higher costs compared to the LIB benchmark. This is mainly due to new manufacturing technologies and smaller-scale production. Development of solid electrolytes and their compatibility with electrolytes is the key for the emerging solid-state batteries. Fig. 2 summarizes the different types of solid electrolytes used in SSBs with a ranking approach for the different properties. It is hard to identify the most promising SSB due to lack of sufficient studies [16].

To ensure the efficient performance of the battery, cell thickness of the electrolyte, its microstructure, and interfaces need to be controlled during material processing and manufacturing. The thickness of the electrolyte has considerable impact on the achievable energy density of the battery cell. The microstructure of the SSBs is critical for establishing transport pathways for the ions as solid-state composite cathodes comprised of cathode material and solid electrolyte. Along with that, interfaces are important as nonuniform or irregular interfaces can lead to local ionic flux that can cause degradation and affect the lifetime of the solid-state batteries [29]. As in the case of state-of-the-art lithium-ion batteries, industrial scale production of SSBs must take into account material criticality. Smith et al. (2021) suggested to explore the sulfide electrolyte based SSBs other than Li$_{6.4}$La$_3$Zr$_{1.4}$Ta$_{0.6}$O$_{12}$ (LLZTO) garnet structured electrolyte considering the issue of material criticality [67]. Wet processing shows a higher maturity for the oxide and sulfide based SSBs and the extrusion-based processing is more mature and used commercially to produce polymer based SSBs [35]. Integration of the various cell components with the scalable fabrication process considering the economic as well as technical aspects poses significant challenges [4]. After all, the commercialization of SSLBs relies upon the development of high-performance thin solid electrolytes [35].

Low ionic conductivity at low temperature along the electrolyte-electrode interface produces s higher interfacial resistance between electrolyte and electrode that hinders the performance of all SSBs. Poor chemical physical and electrochemical compatibility of electrolytes with the electrodes also limits the electrochemical performance of battery cell [68,69]. All three major types of solid electrolytes have different properties, which influence the functioning of solid-state batteries. Han et al. (2020) showed that hybrid solid-state electrolytes (HSEs) combine the advantages of inorganic and polymer electrolytes while overcoming the disadvantages of each component when used separately using the ranking for the different properties as shown in Fig. 2 [70].

Despite several advantages of solid electrolytes over liquid electrolytes, they face a variety of challenges and further research needs to be carried out to address these issues for the commercial success of the SSBs [43]. For large scale application of solid electrolytes in SSBs following attributes are required in the future, for example, (i) high ionic conductivity at RT; (ii) negligible interfacial impedance; (iii) electrolytes should have matching thermal expansion coefficients with both electrodes; (iv) higher chemical stability; (v) wide electrochemical stability window; (vi) low cost and easier methods of synthesis, high throughput, (vii) environmental sustainable, and (viii) availability of the constituent materials for electrolyte production (criticality aspect) [43,48].
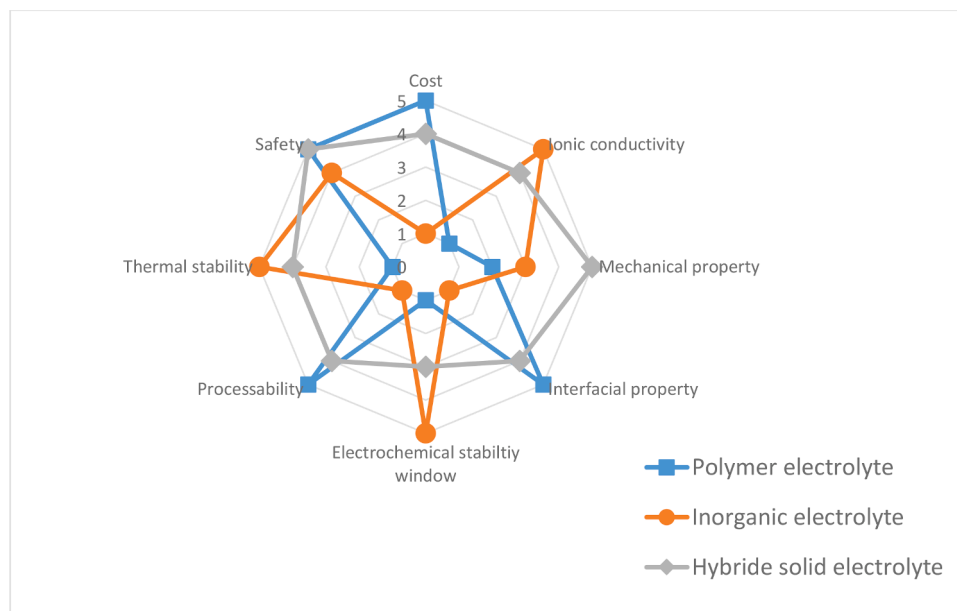
Fig. 2. Ranking of properties of solid electrolytes (5 = best, 1 = worst) (data based on Han et al. (2020).

3. Review of existing LCAs of solid-state batteries

3.1. LCA methodology

Global Life Cycle Assessment (LCA) is a standardized method to analyze potential environmental impacts of a system, product, or service throughout its entire life cycle, from raw materials acquisition to the end-of-life phase. The standard LCA consists of four main phases, which are often interdependent such as goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA) and interpretation. The goal and scope definition provides a description of the product system in terms of the system boundaries and a functional unit. Functional unit is a quantitative description of the service performance of the investigated product system which is the important basis for comparison between different alternative products or services. The inventory Analysis aims to identify and quantify energy, water and materials usage and environmental releases to atmosphere. Impact Assessment involves the assessment of the potential human and ecological effects of energy, water, and material usage and the environmental releases identified in the inventory analysis [71]. Several LCIA methods are being used such as ReCiPe, ILCD, EF etc. They use different impact indicators as e.g., global warming potential (GWP), cumulative energy demand (CED), human ecotoxicity (HT) etc. However, the most preferred indicator used for comparative assessment is GWP. GWP converts LCI data into carbon dioxide equivalents for the emissions such as carbon dioxide (CO_2), nitrogen dioxide (NO_2), methane (CH_4), chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), methyl bromide (CH3Br) etc. Finally, the interpretation phase evaluates the results of the inventory analysis and impact assessment to select the preferred product, process, or service with a clear understanding of the uncertainty and the assumptions used to generate the results. LCA models are very commonly built using existing databases and datasets that provide background life cycle inventory (LCI) data that can (ideally) be coupled with the collected primary data. Primary data are plant-specific, measured, modelled, or estimated data for conducting an LCI that the practitioner can directly access or for which the practitioner has input into the data collection process. Secondary Data are not collected specifically for the purpose of conducting an LCI and for which the practitioner has no input into the data collection process, it can be taken from the various resources form the literature, data sheets or expert inputs. In general, overall LCA methodology can help decision-makers by comparing all

major environmental impacts caused by products, processes, or services [72].

3.2. State of the art

An exhaustive literature research is carried out on available studies with the focus on the environmental life cycle impacts of SSBs. The literature search in google scholar using "solid electrolytes" shows 284,000 hits indicating that a high number of publications concerning solid state electrolyte related research work has been carried out in the same time frame. In sharp contrast, when the literature search in google scholar is done using "LCA on solid state batteries", the result only shows 15,800 hits from 2015 to 2022. Surprisingly, the results show that there are only six detailed LCA studies on SSBs available. In the following part, a general overview on the available studies is provided. This is followed by an analysis of the goals and scopes of the studies, then LCAs are analysed in detail in respect of the used electrolytes.

3.3. Available studies

Though lots of research on the solid-state batteries is being carried out in the last few decades, solid electrolytes still suffer from some of the issues regarding ionic conductivity and compatibility with the electrodes, hindering a broad market introduction. Their low development stage (no industrial scale) and technical challenges as well as the pure absence of robust data represents a challenge for environmental assessment. Consequently, only six studies have been identified which discuss the life cycle impact of production and use of solid-state batteries in a sufficient degree. These studies mostly use assumptions regarding the performance of battery technologies at different stages of their life cycle and have a major focus on mobility applications. Details regarding the cell properties (chemistry, specific energy and battery size), inventory data, function unit, boundary of assessment, different impact categories of the reviewed studies are summarized in Table1.

3.4. Goals and scopes

Six studies are available in the literature on LCA of SSBs and amongst them four studies focus on the potential application for electric mobility and two studies consider the application of SSB for stationary energy storage. Details about these LCA studies are enlisted in Table 2.

Table 1
Details about the LCA studies available in the literature for the solid-state batteries.

Reference	Battery chemistry	Specific energy (Wh/kg)	Battery size	Method of impact assessment	Impact categories analysed	Cycle life	System boundary and regional scope	Functional unit	Cell/battery type
Lastoskie and Dai (2015)	LCO-Li metal LMO-Li metal NCM-Li metal LVO-Li metal SVO-Li metal NCA-Li metal LNMO-Li metal CuMn-Li metal	300 230 270 580 430 220 350 175	40kWh	ReCiPe	CED, GWP, HT, PMF, FE, POF, WDP, MDP	1000 1000 1300 1000 N/A N/A N/A N/A	Cradle to gate United States	1 Wh energy storage	Model cell (cylindrical)
Keshavarzmohammadian et al. (2018)	FeS$_2$+TiS$_2$-Li metal (Sulfur based solid state lithium pyrite battery)	182	80kWh	TRACI version 1.02), developed by the U.S. EPA	ODP, GWP100, PSF, AP, FE, HT, RPE, ETP, CED	N/A (assumed battery lasts the life of Electric vehicle)	Cradle to gate United States	Production of 80 kWh battery pack	Original cell based on lab scale results
Smith et al. (2021)	LFP-Li metal	314	1 kg	ReCiPe Midpoint (H) v1.13 and cumulative energy demand	GWP100, ETP, HT, METP, TETP, FE, ME, AP, CED	100	Cradle to gate UK	1 kg of battery	Model cell
Troy et al. (2016)	LCO-Li metal	26–87	43.75 mAh	ILCD	CED, GWP, HT, PMF, FE, POCP, HT, IP, ET, ODP, RDP, AP	N/A	Cradle to gate Germany	43.75mAh Capacity	Original cell (Pouch)
Vandepaer et al. (2017)	LFP-Graphite	88	75 kWh and 6MWh	IMPACT 2002+ and TRACI	ODP, GWP, AP, FE, HT, FDP, IR	5000	Cradle to gate	Delivery of 1 Mwh of electricity	Original cell
Zhang et al. (2022)	NMC-Lithium metal foil	116.5 (Estimated)	Coin cell of 5.15 gm	TRACI	GWP AP, ETP, EP, HHPA, HTP, ODP, FF, SA	N/A	Cradle to gate (source to wheel)	Coil cell with 100–150 mAh capacity	Original cell (Coin)

CED- Cumulative energy demand, GWP- Global warming potential, HT-Human toxicity, PMF-Particulate matter formation, FE-Freshwater eutrophication, POF- Photochemical oxidant formation, WDP-Water depletion potential, MDP-Mineral depletion potential, POCP- Photochemical ozone formation, IR- Ionizing radiation – Human health effects, ODP-Ozone depletion potential, RDP-Resource depletion potential, AP-Acidification potential, ETP-Ecotoxicity potential, PSF- Photochemical smog formation, METP Marine ecotoxicity potential, TETP- Terrestrial ecotoxicity potential, ME- Marine eutrophication, RPE-Respiratory effects, FRS- Fossil resource scarcity, LU-Land use, MRS-Mineral resource scarcity, WC-Water consumption, FDP-Fossil depletion potential.

Keshavarzmohammadian et al. (2015) analysed environmental impact of lithium pyrite (FeS$_2$) batteries for electric mobility with a range of 200-miles considering the functional unit of 80 kWh of energy capacity with an estimated battery mass of 440 kg. The assessment has a cradle to gate perspective, considering all steps of battery manufacturing process including the material and energy requirements to produce cells, modules, and a final battery pack. It also includes battery materials production, energy for battery material preparation, manufacturing, and assembly; transportation of raw materials to chemical plants and to factories where related components are manufactured; and transportation of materials and prefabricated components to the battery production facilities. Capital equipment and infrastructure (e.g., the stainless steel for the coating machine) for battery production were not included in the assessment [3].

Troy et al. (2016) investigated environmental impacts to produce SSB pouch cells, manufactured at the Institute of Energy and Climate Research (IEK-1) of Research Center Jülich (FZJ). The functional unit is a pouch cell with a capacity of 43.75 mAh. Three scenarios including the production of pouch cells at present laboratory scale production (scenario 1), ideal laboratory scale production with the possible efficiency enhancement (scenario 2), and envisioned industrial scale production

with the assumption of reduction in the energy requirement and the size of the solid electrolyte (scenario 3) were considered in the study [73]. Smith et al. (2021) compared the environmental hotspots of a LIB using LiFePO$_4$ as cathode and an SSB based on solid inorganic garnet structured electrolyte Li$_{6.4}$La$_3$Zr$_{1.4}$Ta$_{0.6}$O$_{12}$ (LLZTO) via a cradle to gate approach. Environmental impacts were compared using two functional units namely i) impacts per kg of battery production and ii) impacts for delivery of 50 MJ of electrical energy [67] and the results indicate a lower environmental impact of LIBs, in particular LFP compared with SSBs.

Vandepaer et al. (2017) compared cradle to gate the environmental performance of lithium metal polymer (LMP) stationary batteries to conventional LFP batteries with the storage capacity of 75 kWh and 6 MWh to capture impacts associated with a distributed and centralized battery system configuration that is intended to be used in Quebec. The study uses 1 MWh of electricity delivery from the used configurations as functional unit. The boundary of the assessment includes raw material extraction, manufacturing, installation and the maintenance of battery and other components. It also considers the use phase to deliver the stored electricity along with the end of life treatments as a landfill considering the transportation to a treatment facility [74]. Lastoskie and

Table 2
Details of the data sources for the electrolyte and battery cell used in the previous LCA studies.

Reference	Type of Electrolyte	Data type	Data sources Electrolyte	Development status	Type of modeling	Sources	Data availability	Comments
Lastoskie and Dai (2015)	Ceramic inorganic electrolyte LiPON	Primary (modelled using Battery Design Studio) and (Wang and Sastry, 2014).	Schaefer et al., (2012)[78]	Low TRL Lab Scale	Bottom up	Eco invent database	Most LCI data is available But not able to use for recalculation	LiPON based SSBs have very low ionic conductivity. Only suitable for micro batteries for e.g., medical devices
Keshavarzmohammadian et al. (2018)	Li_2S and P_2S_5 as the sulfide based solid electrolyte	Primary Lab-scale production processes obtained from solid power company in 2017. Pyrite battery pack is modelled using the Argonne National Laboratory (ANL) BatPac model (2016) and Nelson et al. (2012) [79]	Yersak et al., (2013)[80]	Low TRL Lab Scale	Bottom up	US-EI 2.2 LCI database	Full LCI data available	Pyrite based SSBs have made considerable progress, but there are still open challenges, especially regarding the lithium metal anode and the electrochemical stability of the sulfide solid electrolytes.
Smith et al. (2021)	$Li_7La_3Zr_2O_{12}$ (LLZO) garnet-structured electrolyte	Secondary data collected from Du et al. (2015) [81], Li et al. (2014) [82], Shi et al. (2018) [83], Choi et al. (2013) [84] and from Functional Materials and Devices Laboratory, University of Sheffield.	Du et al. (2015) [81], and Li et al. (2014) [82]	Low TRL Lab Scale	Bottom up	Eco invent database	Full LCI data available	Electrolyte production contributes major impacts due to the high temp sintering process during manufacturing. Other methods such as cold sintering needs to be explored to lower the environmental impacts
Troy et al. (2016)	Lithium lanthanum zirconate (LLZO) $(Li_7La_3Zr_2O_{12})$	Primary data for the lab scale manufactured at the Institute of Energy and Climate Research (IEK-1) of Research center Julich (FZJ).	Research Center Julich (FZJ)	Low TRL Lab Scale	Bottom up	GaBi6 and Eco invent database	Full LCI data is not available	LLZO electrolyte production accounts major energy consumption. But the future technology development and scaling effect will help to reduce the environmental impacts.
Vandepaer et al. (2017)	Porous polymer electrolyte	Primary data from industrial partners' information and from previous studies and reports as well as	LMP battery manufacturer (Industrial partner)	High TRL Industrial scale	Bottom up	Eco invent 3.1	Full LCI data is not available	Details of the polymer electrolyte has not been given in the article. Polymer based SSBs shows lower ionic conductivity at lower temperatures hence it faces operational challenge.
Zhang et al. (2022)	Inorganic electrolyte LATP	Primary data Coin cell is produced at lab scale using process by Yoshinari et al. (2019) [85].	Lab scale production using Liu et al. (2017) [86] and Key et al. (2012) [87].	Low TRL Lab Scale	Bottom up	Eco invent 3.1	Full LCI data available	ASSB with inorganic electrolyte LATP shows higher environmental impact but the improvement in energy efficiency with lowering the thickness of the electrolyte will help to reduce the environmental impact with the technological development.

Dai (2015) have carried out a comparative cradle to gate based LCA of laminated lithium ion and vacuum vapor-deposited thin film SSBs. The focus of the assessment was to analyze major impacts for a passenger battery electric vehicle (BEV) to deliver 120,000 miles considering a ten-year duration on U.S. roadways. Three laminated and eight solid state chemistries using functional unit of 1 Wh of energy storage were compared in the study. It does not include impacts associated with machinery and vehicles used for transport of materials. In contrast machinery consumption of electricity and natural gas and freighter energy consumption of fuels for battery pack manufacturing and assembly

using the Eco invent 2.2 standard transport distance for Europe are included [75]. Zhang et al. (2022) investigated within a cradle to gate assessment of all SSLB cell using $Li_{1.3}Al_{0.3}Ti_{1.7}(PO_4)_3$ (LATP) inorganic solid electrolyte (ISE) and compared it with a lithium-ion coin cell. The assessment aims to identify the environmental hotspots over the different life cycle stages and includes all the processing steps for the fabrication of coin cells [76]. Recently, Larrabide, et al. (2022) analyzed the environmental impact of solid polymer electrolytes for SSLB. This study compared cradle to gate environmental impacts for six different solid polymer electrolytes on a pilot scale production level. This study provides useful insights for the technology developer for the selection of suitable solid electrolytes at an early stage of the development out of an environmental perspective. The life cycle inventory data for these polymer electrolyte production will be helpful for the further investigation in LCA studies for the different combinations of emerging SSBs [77].

Overall, the environmental impacts of the six reviewed studies are expressed in terms of different functional units that make it difficult to compare the results. Also, along with that, the system boundaries, different types of assessed battery chemistries pose a challenge regarding comparability.

3.5. Sources of inventory data

An overview of inventory data and details such as development status, data availability, type of modeling (bottom-up vs. top-down) and type of electrolyte are provided in Table 2. The magnitude of the studies does not provide the complete inventory data. Hence, finding reliable and accurate data for emerging battery technologies is a difficult task.

Vandepaer et al. (2017) compares the performance of Li-ion and Lithium metal polymer stationary batteries (LMP). Here lithium iron phosphate (LFP) is used as a cathode with graphite as anode in LIBs, and a new polymer-based electrolyte is used in lithium metal battery. Eco invent 3.1 was used as the source of background LCI data. The data for the battery periphery, such as battery container, maintenance, monitoring of the system along with the LFP cathode chemistry for the battery were obtained from the literature. LMP primary data was provided by a battery manufacturer and details regarding that are not provided in the study [74]. Keshavarzmohammadian et al. (2018) used primary inventory data for a solid electrolyte on a lab scale level production from Yersak et al. (2013) [80].Here, a prospective LCA has been carried out using a process-based attributional approach due to the low TRL of SSB. The data for the energy demand of module and pack assembly was taken from Nelson et al. (2012) [79]. Battery production process data for the assessment is taken from laboratory data, U.S. patents, literature data and US-EI 2.2 database for the life cycle inventory of the materials and energy required for the battery along with the assembly processes [3].

Another study carried out by Lastoskie, and Dai (2015) analyzed three different cathode active materials for laminated cells while for the solid-state cells eight cathode layer chemistries were considered. Battery design studio was used to generate the material composition of the single lithium-ion cell while SSB cell design data was provided by the private company Sakti3 (subsidiary of Dyson). Most of the inventories were constructed using the precursors for the electrolyte and electrodes assumed. The data for this was taken for the precursors by reported synthesis methods from various literature studies. For the SSBs (LiPON) lithium phosphorus oxynitride was used as the glass-ceramic electrolyte with the lithium anode. Data for the solid electrolyte was taken from Schaefer et al. (2012). SSB energy density of the cathode layer was assumed to be double compared to the same cathode material in a laminated cell [78].

Along with LIPON solid electrolyte, lithium lanthanum zirconate (LLZ) electrolyte was also considered as most promising candidate for SSB technology applications in Troy et al. (2016). Here the authors developed an SSB pouch cell using lithium metal as anode, a $LiCoO_2$/$Li_7La_3Zr_2O_{12}$ (LCO/LLZ) mix-cathode, separated by a $Li_7La_3Zr_2O_{12}$

(LLZ) electrolyte at their own facility at the Institute of Energy and Climate Research (IEK-1) of the Research Center Jülich (FZJ), for a laboratory scale process. Details of the inventory data for the pouch cell including the solid electrolyte LLZ were not provided in the publication. Specific energy for the batteries mentioned in the Troy et al. (2016) is in a range of 26–87 Wh/kg that is due to scale of the operation. Energy density of the cell at laboratory scale is estimated to be 26 Wh/kg while assuming industrial scale production scenario with optimized packaging, the energy density of the cell is estimated to be 87 Wh/kg [73]. $Li_{6.4}La_3Zr_{1.4}Ta_{0.6}O_{12}$ (LLZTO) garnet structured solid electrolyte was used for SSB and compared with a LiB by Smith et al. (2021). The LCI of the LiB was modelled via the ANL BatPac model while that of the SSB was derived from both literature studies, on-going Li-ion projects at the Functional Materials and Devices Laboratory, Materials Science and Engineering, University of Sheffield. LFP battery chemistry has been used for both types of batteries [67]. Zhang et al. (2022) used $Li_{1.3}Al_{0.3}Ti_{1.7}(PO_4)_3$ (LATP) inorganic solid electrolyte (ISE) to produce a coin cell and the synthesis of LATP based on Key et al. (2012). The study considered a lithium nickel manganese cobalt oxide (NMC) cathode, LATP as solid electrolyte, and a metallic lithium foil as anode. The fabrication of the coin cell is based on their experimental data using direct measurements. Inventory details for the coin cells are available in the supporting information of the article [76].

Overall, for some of the available studies, inventory data, including all relevant downstream and upstream processes are available. Along with that existing lab-scale cells have been used whilst some studies modelled the cells with assumptions regarding the performance as well as the energy density. As mentioned before, SSB are still in the developing phase, so high uncertainties regarding their technical performance have to be taken into account. Also, results are sensitive to different input material/processes. Hence it becomes necessary to conduct uncertainty analysis to account the variation in the inventory data.

3.6. LCA results from existings studies on solid state batteries

As stated before, the results provided in the analysed studies are very dependent on many factors, such as the energy demand and material supply for manufacturing. Additionally, most of the data come from a lab scale with high uncertainties, including the use of chemicals and other materials that can potentially impact the LCA results [88]. Impact of the other key assumptions such as battery performance, efficiency, energy density, calendrical and cycle life have considerable impact on LCA results. For some of the studies detailed inventory data is also not available, making it difficult to compare manufacturing energy and material demand for SSB. Most significantly, the use of multiple functional units for the comparative assessments along with the use of different impact assessment methodology creates differences in the LCA results. Some of the common impact indictors such as global warming potential (GWP) and cumulative energy demand (CED) can be compared but the normalization of the results needs to be carried out using a similar functional unit. All of the reviewed studies use different impact assessment methods, with global warming potential being the most used indicator. Consequently, it is used here for the sake of comparability. In line with this different functional units of each study were normalized using a reverse engineering approach. Fig 3. shows the comparative global warming potential impacts for the existing LCA studies on SSB available in the literature. But with the availability of more LCA studies on SSBs future assessments should provide a comparison of other categories such as human toxicity and other relevant impact categories.

The GWP impacts for these studies were normalized using a functional unit of 1 Wh of energy storage capacity to allow some degree of consistent comparison. Error bar stands for the different alternatives analysed in the different available LCA studies on SSBs. Lastoskie and Dai (2015) calculated a GWP 0.03–0.058 kg of CO_2 equivalents per Wh storage of energy for different SSB chemistries in a cylindrical format.
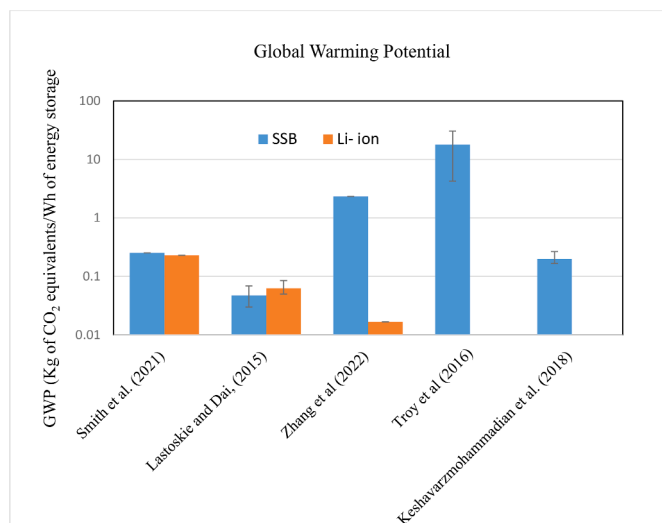
Fig. 3. Comparative life cycle global warming impact for the available LCA studies on solid state batteries.

The ReCiPe methodology was used for the impact assessment.

Troy et al. (2015) calculated a GWP of 0.2–5.4 kg of CO_2 eq. to produce a SSB pouch cell with 43.75mAh capacity using International Reference Life Cycle Data System (ILCD) for impact assessment. Here different scales from laboratory production to potential industrial scale production with the assumptions in potential improvement in the process have been considered which are shown in error bar in the Fig. 3. Vandepaer et al. (2017) showed GWP of 20.5–25.6 kg of CO_2 equivalent for the stationary application of a limital polymer battery with a capacity of 6 MWh and 75 kWh. The authors used the impact assessment method IMPACT 2002+ and used 14 midpoint categories and four endpoint categories for the assessment. Other studies for the inorganic solid-state batteries illustrated the life cycle impact for GWP of 0.103 gm of CO_2 eq./km for coin cell by Zhang et al. (2022) and 79.11 kg of CO_2/ kg of SSB production by Smith et al. (2021).

As mentioned before, the comparison between different LCA studies for SSB technologies becomes difficult due to the differences related to the functional unit, boundary of assessment, impact assessment methodology etc. Overall LCA results for emerging SSBs are very sensitive to the various factors such as the type of electrolyte, scale of the operation/ processing, their technology readiness level and performance in the battery system. Current solid-state batteries are still in the developmental phase showing life cycle GWP in the range 0.1–18 kg of CO_2/Wh (Fig. 3) which are higher comparing with the conventional lithium-ion batteries 0.025–0.35 kg of CO_2/Wh [1]. More recent literature as Peters et al. (2021) analyzed the life cycle environmental impacts of sodium ion batteries and showed global warming potential impacts from 0.05 to 0.09 kg of CO_2/Wh of cell storage capacity for the different cell chemistries [14]. Deng et al. (2017) evaluated life cycle global warming potential impacts for lithium sulfur batteries, which are 0.17 kg of CO_2/Wh of cell energy storage. In relation to that emerging solid-state batteries have comparatively higher environmental impacts due to low TRL stages comparing with the existing batteries [89].

4. Discussion

The literature review revealed that there are only six publications on LCAs of solid-state battery technologies available that provide sufficient in-depth analysis. This section discusses the discrepancies in comparative assessment of LCA studies of emerging SSB technologies and proposes the unification methodology for LCA to address these discrepancies for a fair comparative assessment.

4.1. Identification of discrepancies involved in existing LCA studies

It has been observed that the comparison of different LCA studies on SSBs and corresponding results becomes difficult, due to (i) the heterogeneity observed in the goal and scope and resulting functional unit, (ii) boundary of assessment as well as different battery chemistries adopted in the studies, (iii) source of life cycle inventories and life cycle impact analysis methods and finally (iv) the level of details in modeling.

The heterogeneity (i) or non-uniformness between available studies at the different stages in turn shows inconsistencies in the LCA results. Naturally, goals and scope of the available LCA studies on SSBs shows differences, which is not avoidable in the field of LCA. Each study uses distinctive chemistries, considering different applications and consequently different functional units. Vandepaer et al. (2017) for example focuses on stationary energy storage for distributed and centralized cases while other studies focus on the SSBs potential application for mobility purposes. Regarding the system boundaries (ii) Lastoskie and Dai (2015) considers the battery production along with the use phase for modelled cells with different battery chemistries such as LCO, LMO, NCM, NCA, LNMO etc. and Vandepaer et al. (2017) also considers the production and use phase of the battery production for the different energy storage applications for lithium metal polymer batteries. While for other studies such as Troy et al. (2016), Keshavarzmohammadian et al. (2018) Smith et al. (2021) considers the battery production phase only for the LCO-Li metal, sulfur based solid state lithium pyrite battery and LFP-Li metal battery chemistries.

Regarding iii) some of the studies provide complete original inventory data while few studies provide only partial data due to confidentially perspectives. Consistent recompilation of these inventory datasets with needed reasonable assumptions will reduce the discrepancies in the assessment. Additionally, the scale of battery production and applied impact assessment methodology makes comparability even more challenging. Troy et al. (2016) uses ILCD method, Lastoskie and Dai (2015) uses ReCiPe Midpoint (H) v1.13 and cumulative energy demand and Vandepaer et al. (2017) uses IMPACT 2002+ and TRACI method as indicated in Table 1.

The modeling (iv) of some of the key components for the battery technologies is carried out differently in the available LCA studies. Different assumptions made at different stages will have a large impact as solid-state battery technology is still immature. Comparison of these LCA studies on solid state batteries is possible by addressing the abovementioned issues. Furthermore, uncertainties regarding the issues such as energy density, cycle life, calendrical cycle, its potential application etc. also impact LCA results. These are the main hurdles for a meaningful comparison of the results between the studies.

Overall, the SSB inventory datasets provided by the studies of are not sufficient to reproduce results. Therefore more research on LCA of SSBs is needed for a more generalised environmental impact of SSB categories using e.g. parametric approaches as in the case of by Peters et al. (2021) for sodium ion batteries under a full life cycle perspective using a cellchemistry specific modeling approach [14]. In line with this, also detailed LCI as well model descriptions should accordingly be made available.

4.2. Suggested future solution and challenges for LCA comparison

Comparative assessment of emerging technologies faces several challenges. One of the major limitations for carrying out LCA is the lack of robust and detailed inventory data and uncertainties associated with it. It is thus utmost important to have collaboration with technology developers especially for emerging technologies such as SSB. Many times, it is difficult to get the primary inventory data due to confidentiality or simply the absence of the same. Another aspect is the technology readiness level of emerging SSB, which increases the uncertainty of the inventory data due to the absence of any performance data of the developing technology. Comparative assessment of the existing LCA

studies on SSBs using a consistent basis is required for the further improvement in the research from the environmental perspective [39]. With the consideration of identified discrepancies, a common base is needed to improve the comparability by simplifying the assumptions or inventory in the different studies in a general way as shown in Fig. 4.

Fig. 4 explains the detailed procedure to unification methodology for the comparative assessment of emerging technologies like solid state batteries. Firstly, the goal and scope for all the available LCA studies are defined with the consistent functional unit. After that a unification of inventories is done at different levels. To do so life cycle inventories have to be Inventories are recompiled and be used as a common base and implemented in the further assessment. The corresponding uncertainty with the original LCI must be considered. As different battery chemistries are being used with different types of solid electrolytes for the emerging SSB technologies, the recognition of maximum number of common parts and the differences must be considered for the comparative assessment of the available studies. Regarding the source of energy supply and energy demand for production of battery cell the average value should be calculated from all studies. Along with those major differences between battery chemistries and production technologies has also to be considered for making fair comparison [2].

Electricity mix varies for the different LCA case studies and thus the associated impacts associated with it also varies accordingly. From the available LCA studies on emerging technologies such as manufacturing of solid-state batteries, it is important to have consistent electricity mixes used for the fair comparison of the emerging technologies. However, batteries are being manufactured in different countries, with a specific electricity mix. Consequently, to improve the comparability, the same electricity mix has to be used. For e.g., Schmidt et al. (2019) estimated the life cycle GHG emissions for the stationary energy storage using battery technologies and also discussed the associated differences in life cycle GHG emissions due to different locations for different countries [90]. Montenegro et al. (2021) demonstrated the effect of the electricity mix on the environmental impacts associated with magnesium battery production for different countries [91]. Then the quality of results can be improved to represent the regional or local electricity mix. Unified inventories can also be used for all battery chemistries by generating detailed disaggregated inventory data representing the actual market mix while maintaining comparability. With the unified inventory from all the studies such as battery management system (BMS) and pack housing the battery mass changes, and this affects the battery energy density and thus the results per kWh of energy storage capacity. But the impact with the unified energy density and the original density can be compared to check the discrepancy in the results. The modeling of the recompiled LCI is done by using the same LCA software and inventory database to avoid the inconsistency associated with the original LCI for different studies [2].

Prospective life cycle assessments for emerging battery technologies have by nature uncertainties due to assumptions at various life cycle stages compared to the LCAs for established products or processes. But it provides guidance for sustainable design and upscaling before the potential commercialization of a SSB. The results are bound to assumptions, uncertainties and assumptions so the sensitivity analysis with key input assumptions will provide the broader picture of the technology or processes.

Currently the SSBS are at very early technology development stage,
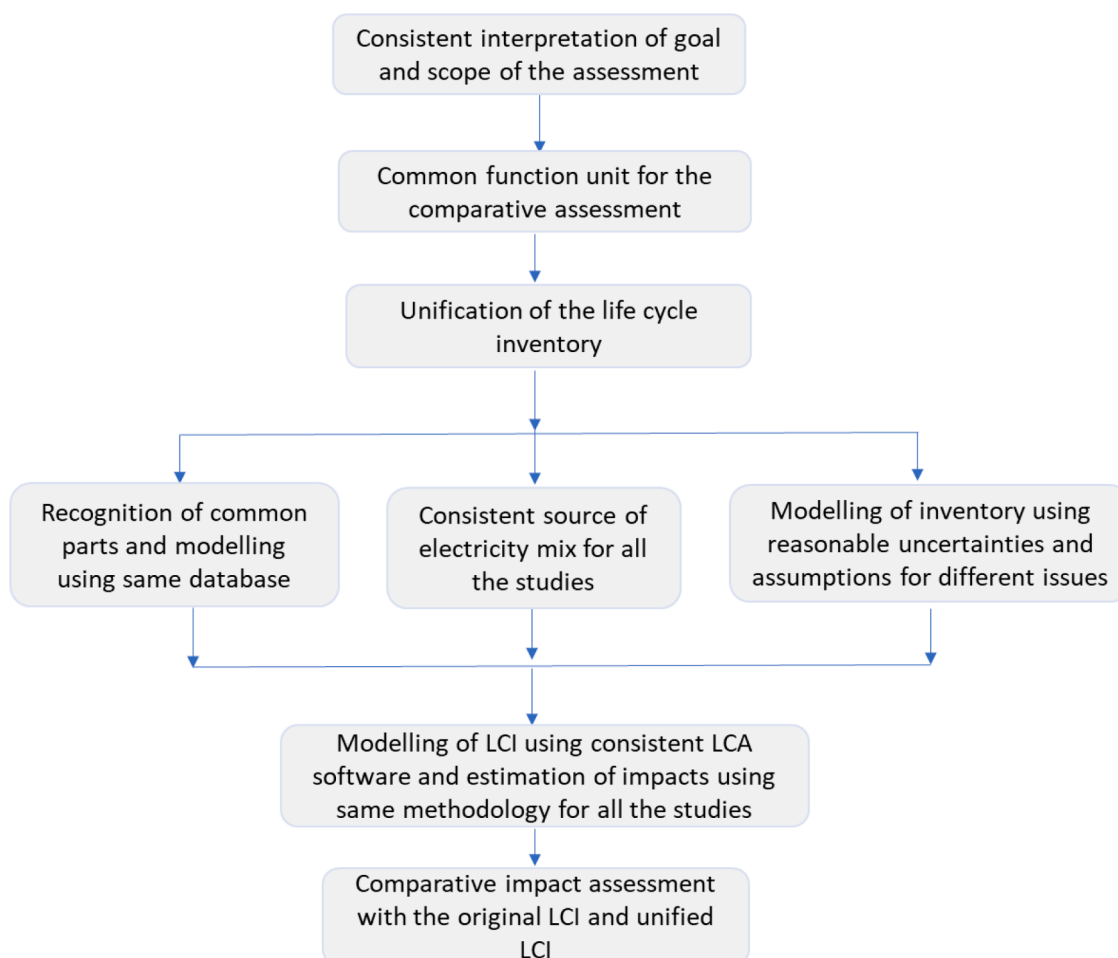

Fig. 4. Framework for unification methodology for the comparative assessment of emerging technology.

where not much of the data is available for the post processing such as recycling (end of life phase) of materials. Consequently, there is also no detailed description available in literature. Only with the availability of such data it would be possible to analyze and compare the end of life phases of the batteries

5. Conclusions

SSBs are considered as one of the most promising future battery technologies. Still, there are several technological constraints for the utilization of SSBs for commercial mobility as well as stationary energy storage applications that have to be addressed within further research. The presented review focuses on technical aspects and the critical assessment of the existing LCA studies on solid state batteries. SSBs are at a very early stage of development, with active research and ongoing proof of concepts on the laboratory scale from TRL 4–7.

The comparisons of LCA results of different studies are difficult and should not be executed without addressing discrepancies regarding diverse system boundaries, functional units, background data, and impact methodologies. Therefore, the described unification methodology is proposed for a comparison of different LCA studies on a consistent basis, although this is not possible due the limited data availability so far. The proposed methodology for the evaluation of environmental hotspots for emerging SSBs can be potentially applied for existing LCA studies, if detailed LCIs are available using the present unification approach. This would help to compare the different available LCAs for SSBs on a consistent basis. In general, the prospective sustainability assessment of emerging technologies as SBB is considered as highly important to support early stages of the technology development and design.

Declaration of Competing Interest

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.

Data availability

I have used data avaialble in open literature

References

[1] J.F. Peters, M. Baumann, B. Zimmermann, J. Braun, M. Weil, The environmental impact of Li-Ion batteries and the role of key parameters – a review, Renew. Sustain. Energy Rev. 67 (2017) 491–506.

[2] J.F. Peters, M. Weil, Providing a common base for life cycle assessments of Li-Ion batteries, J. Clean. Prod. 171 (2018) 704–713.

[3] A. Keshavarzmohammadian, S.M. Cook, J.B. Milford, Cradle-to-gate environmental impacts of sulfur-based solid state lithium batteries for electric vehicle applications, J. Clean. Prod. 202 (2018) 770–778.

[4] N. Boaretto, I. Garbayo, S. Valiyaveettil-Sobhan Raj, A. Quintela, C. Li, M. Casas-Cabanas, F. Aguesse, Lithium solid-state batteries: state-of-the-art and challenges for materials, interfaces and processing, J Power Sources 502 (2021), 229919.

[5] Global EV Outlook, 2021: Accelerating Ambitions Despite the Pandemic, International Energy Agency, 2021, pp. 1–101.

[6] International Energy, Outlook 2016 With Projections to 2040, U.S. Energy Information Administration, 2016, pp. 1–290.

[7] C. Wu, J. Lou, J. Zhang, Z. Chen, A. Kakar, B. Emley, Q. Ai, H. Guo, Y. Liang, J. Lou, Y. Yao, Z. Fan, Current status and future directions of all-solid-state batteries with lithium metal anodes, sulfide electrolytes, and layered transition metal oxide cathodes, Nano Energy 87 (2021), 106081.

[8] X.-G. Yang, T. Liu, C.-Y. Wang, Thermally modulated lithium iron phosphate batteries for mass-market electric vehicles, Nature Energy 6 (2021) 176–185.

[9] E. Quartarone, P. Mustarelli, Electrolytes for solid-state lithium rechargeable batteries: recent advances and perspectives, Chem. Soc. Rev. 40 (2011) 2525–2540.

[10] K. Takada, Progress and prospective of solid-state lithium batteries, Acta Mater. 61 (2013) 759–770.

[11] J.L. Sullivan, L. Gaines, Status of life cycle inventories for batteries, Energy Convers. Manage. 58 (2012) 134–148.

[12] C.M. Costa, J.C. Barbosa, R. Gonçalves, H. Castro, F.J. DelCampo, S. Lanceros-Méndez, Recycling and environmental issues of lithium-ion batteries: advances, challenges and opportunities, Energy Storage Mater. 37 (2021) 433–465.

[13] S. Ziemann, D.B. Müller, L. Schebek, M. Weil, Modeling the potential impact of lithium recycling from EV batteries on lithium demand: a dynamic MFA approach, Resour. Conserv. Recycl. 133 (2018) 76–85.

[14] J.F. Peters, M. Baumann, J.R. Binder, M. Weil, On the environmental competitiveness of sodium-ion batteries under a full life cycle perspective – a cell-chemistry specific modelling approach, Sustain. Energy Fuels 5 (2021) 6414–6429.

[15] P. Dechent, A. Epp, D. Jöst, Y. Preger, P.M. Attia, W. Li, D.U. Sauer, ENPOLITE: comparing lithium-ion cells across energy, power, lifetime, and temperature, ACS Energy Lett. 6 (6) (2021) 2351–2355.

[16] Report on Solid-State Battery Roadmap 2035+, Fraunhofer (2022) 1–122.

[17] H. Dai, Y. Chen, W. Xu, Z. Hu, J. Gu, X. Wei, F. Xie, W. Zhang, W. Wei, R. Guo, G. Zhang, A review of modification methods of solid electrolytes for all-solid-state sodium-ion batteries, Energy Technol. 9 (1–9) (2021), 2000682.

[18] R. Hausbrand, G. Cherkashinin, H. Ehrenberg, M. Gröting, K. Albe, C. Hess, W. Jaegermann, Fundamental degradation mechanisms of layered oxide Li-ion battery cathode materials: methodology, insights and novel approaches, Mater. Sci. Eng. B 192 (2015) 3–25.

[19] B. Scrosati, J. Garche, Lithium batteries: status, prospects and future, J J. Power Sources 195 (2010) 2419–2430.

[20] M. Iturrondobeitia, O. Akizu-Gardoki, R. Minguez, E. Lizundia, Environmental Impact Analysis of Aprotic Li-O$_2$ Batteries Based on Life Cycle Assessment, ACS Sustain. Chem. Eng. 9 (2021) 7139–7153.

[21] D. Aurbach, E. Zinigrad, Y. Cohen, H. Teller, A short review of failure mechanisms of lithium metal and lithiated graphite anodes in liquid electrolyte solutions, Solid State Ionics 148 (2002) 405–416.

[22] S. Ferrari, M. Falco, A.B. Muñoz-García, M. Bonomo, S. Brutti, M. Pavone, C. Gerbaldi, Solid-state post Li metal ion batteries: a sustainable forthcoming reality? Adv. Energy Mater. (1–30) (2021), 2100785.

[23] S. Xia, X. Wu, Z. Zhang, Y. Cui, W. Liu, Practical challenges and future perspectives of all-solid-state lithium-metal batteries, Chem 5 (4) (2019) 753–785.

[24] L. Zhou, N. Minafra, W.G. Zeier, L.F. Nazar, Innovative approaches to Li-argyrodite solid electrolytes for all-solid-state lithium batteries, Acc. Chem. Res. 54 (2021) 2717–2728.

[25] R. Sacchi, C. Bauer, B.L. Cox, Does size matter? The influence of size, load factor, range autonomy, and application type on the life cycle assessment of current and future medium- and heavy-duty vehicles, Environ. Sci. Technol. 55 (2021) 5224–5235.

[26] F. Hao, F. Han, Y. Liang, C. Wang, Y. Yao, Architectural design and fabrication approaches for solid-state batteries, MRS Bulletin 43 (2018) 775–781.

[27] J. Schnell, T. Günther, T. Knoche, C. Vieider, L. Köhler, A. Just, M. Keller, S. Passerini, G. Reinhart, All-solid-state lithium-ion and lithium metal batteries – paving the way to large-scale production, J. Power Sources 382 (2018) 160–175.

[28] W. Lu, M. Xue, C. Zhang, Modified Li7La3Zr2O12 (LLZO) and LLZO-polymer composites for solid-state lithium batteries, Energy Storage Mater. 39 (2021) 108–129.

[29] S. Randau, D.A. Weber, O. Kötz, R. Koerver, P. Braun, A. Weber, E. Ivers-Tiffée, T. Adermann, J. Kulisch, W.G. Zeier, F.H. Richter, J. Janek, Benchmarking the performance of all-solid-state lithium batteries, Nature Energy 5 (2020) 259–270.

[30] R. Sahore, Z. Du, X.C. Chen, W.B. Hawley, A.S. Westover, N.J. Dudney, Practical considerations for testing polymer electrolytes for high-energy solid-state batteries, ACS Energy Lett. 6 (2021) 2240–2247.

[31] Towards the_battery_of_the_future, Sci. Environ. Policy Eur. Comm. (2018) 1–40.

[32] K.B. Hatzell, Y. Zheng, Prospects on large-scale manufacturing of solid-state batteries, MRS Energy Sustain. 8 (2021) 33–39.

[33] K.V. Kravchyk, F. Okur, M.V. Kovalenko, Break-even analysis of all-solid-state batteries with Li-Garnet solid electrolytes. ACS Energy Lett. 6 (6), (2021) 1–6.

[34] D. Karabelli, K.P. Birke, M. Weeber, A performance and cost overview of selected solid-state electrolytes: race between polymer electrolytes and inorganic sulfide electrolytes, Batteries 7 (18) (2021) 1–13.

[35] X. Yang, K.R. Adair, X. Gao, X. Sun, Recent advances and perspectives on thin electrolytes for high-energy-density solid-state lithium batteries, Energy Environ. Sci. 14 (2021) 643–671.

[36] J. Schnell, F. Tietz, C. Singer, A. Hofer, N. Billot, G. Reinhart, Prospects of production technologies and manufacturing costs of oxide-based all-solid-state lithium batteries, Energy Environ. Sci. 12 (2019) 1818–1833.

[37] Q. Zhao, S. Stalin, C.-.Z. Zhao, L.A. Archer, Designing solid-state electrolytes for safe, energy-dense batteries, Nat. Rev. Mater. 5 (2020) 229–252.

[38] G. Ferraresi, M. El Kazzi, L. Czornomaz, C.-.L. Tsai, S. Uhlenbruck, C. Villevieille, Electrochemical performance of all-solid-state li-ion batteries based on garnet

electrolyte using silicon as a model electrode, ACS Energy Lett. 3 (2018) 1006–1012.

[39] W. Zhao, J. Yi, P. He, H. Zhou, Solid-state electrolytes for lithium-ion batteries: fundamentals, challenges and perspectives, Electrochem. Energy Rev. 2 (2019) 574–605.

[40] D.E. Fenton, J.M. Parker, P.V. Wright, Complexes of alkali metal ions with poly (ethylene oxide), Polymer (Guildf) 14 (11) (1973) 589.

[41] H. Zhang, M. Armand, History of solid polymer electrolyte-based solid-state lithium metal batteries: a personal account, Isr. J. Chem. 61 (2021) 94–100.

[42] J. Castillo L. Qiao, A. Santiago, X. Judez, A. S.Buruaga, G. Jiménez-Martín, M. Armand, H. Zhang, C. Li, Perspective of polymer-based solid-state Li-S batteries, Energy Mater. 2 (1–18) (2022), 200003.

[43] K.J. Huang, G. Ceder, E.A. Olivetti, Manufacturing scalability implications of materials choice in inorganic solid-state batteries, Joule 5 (2021) 564–580.

[44] Y. Wang, S. Song, C. Xu, N. Hu, J. Molenda, L. Lu, Development of solid-state electrolytes for sodium-ion battery-A short review, Nano Mater. Sci. 1 (2019) 91–100.

[45] J. Kalhoff, G.G. Eshetu, D. Bresser, S. Passerini, Safer electrolytes for lithium-ion batteries: state of the art and perspectives, Chem. Sus. Chem. 8 (2015) 2154–2175.

[46] R.C. Agrawal, G.P. Pandey, Solid polymer electrolytes: materials designing and all-solid-state battery applications: an overview, J. Phys. D: Appl. Phys. 41 (1–18) (2008), 223001.

[47] C. Sun, J. Liu, Y. Gong, D.P. Wilkinson, J. Zhang, Recent advances in all-solid-state rechargeable lithium batteries, Nano Energy 33 (2017) 363–386.

[48] R. Chen, W. Qu, X. Guo, L. Li, F. Wu, The pursuit of solid-state electrolytes for lithium batteries: from comprehensive insight to emerging horizons, Mater. Horiz. 3 (2016) 487–516.

[49] C. Li, Z. Wang, Z. He, Y. Li, J. Mao, K. Dai, C. yan, J. Zheng, An advance review of solid-state battery: challenges, progress and prospects, Sustain. Mater. Technol. 29 (2021) e00297.

[50] X. Liu, X. Li, H. Li, H.B. Wu, Recent progress of hybrid solid-state electrolytes for lithium batteries, Chem. Eur. J. 24 (2018) 18293–18306.

[51] L.-.Z. Fan, H. He, C.-.W. Nan, Tailoring inorganic–polymer composites for the mass production of solid-state batteries, Nat. Rev. Mater. 6 (2021) 1003–1019.

[52] J. Li, C. Ma, M. Chi, C. Liang, N.J. Dudney, Solid electrolyte: the key for high-voltage lithium batteries, Adv. Energy Mater. 5 (1–6) (2015), 1401408.

[53] X. Zhang, T. Liu, S. Zhang, X. Huang, B. Xu, Y. Lin, B. Xu, L. Li, C.-.W. Nan, Y. Shen, Synergistic coupling between $Li_{6.75}$ La_3 $Zr_{1.75}$ $Ta_{0.25}$ O_{12} and Poly(vinylidene fluoride) Induces high ionic conductivity, mechanical strength, and thermal stability of solid composite electrolytes, J. Am. Chem. Soc. 139 (2017) 13779–13785.

[54] F. Han, J. Yue, C. Chen, N. Zhao, X. Fan, Z. Ma, T. Gao, F. Wang, X. gao, C. Wang, Interphase Engineering enabled all-ceramic lithium battery, Joule 2 (2018) 497–508.

[55] X. Tao, Y. Liu, W. Liu, G. Zhou, J. Zhao, D. Lin, C. Zu, O. Sheng, W. Zhang, H.-.W. Lee, Y. Cui, Solid-state lithium–sulfur batteries operated at 37°C with composites of nanostructured Li_7 La_3 Zr_2 O_{12} /carbon foam and polymer, Nano Lett 17 (2017) 2967–2972.

[56] Y. Liu, B. Li, H. Kitaura, X. Zhang, M. Han, P. He, H. Zhou, Fabrication and performance of all-solid-state Li–air battery with SWCNTs/LAGP cathode, ACS Appl. Mater. Interf. 7 (2015) 17307–17310.

[57] A. Hayashi, A. Sakuda, M. Tatsumisago, Development of sulfide solid electrolytes and interface formation processes for bulk-type all-solid-state Li and Na batteries, Front. Energy Res. 4 (2016) 1–13.

[58] Z. Yu, S.-.L. Shang, D. Wang, Y.C. Li, H.P. Yennawar, G. Li, H.-.T. Huang, Y. Gao, T. E. Mallouk, Z.-.K. Liu, D. Wang, Synthesis and understanding of $Na_{11}Sn_2PSe_{12}$ with enhanced ionic conductivity for all-solid-state Na-ion battery, Energy Storage Mater 17 (2019) 70–77.

[59] Z. Deng, J. Gu, Y. Li, S. Li, J. Peng, X. Li, J. Luo, Y. Haung, C. Fang, Q. Li, J. Han, Y. huang, Y. Zhao, Ca-doped $Na_2Zn_2TeO_6$ layered sodium conductor for all-solid-state sodium-ion batteries, Electrochim. Acta 298 (2019) 121–126.

[60] H. Hou, Q. Xu, Y. Pang, L. Li, J. Wang, C. Zhang, C. Sun, Efficient storing energy harvested by triboelectric nanogenerators using a safe and durable all-solid-state sodium-ion battery, Adv. Sci. 4 (1–5) (2017), 1700072.

[61] S. Gandi, V.S. Chidambara Swamy Vaddadi, S.S. Sripada Panda, N.K. Goona, S. R. Parne, M. Lakavat, A. Bhaumik, Recent progress in the development of glass and glass-ceramic cathode/solid electrolyte materials for next-generation high capacity all-solid-state sodium-ion batteries: a review, J. Power Sources 521 (1–21) (2022), 230930.

[62] Y. Yan, J.B. Grinderslev, M. Jørgensen, L.N. Skov, J. Skibsted, T.R. Jensen, Ammine magnesium borohydride nanocomposites for all-solid-state magnesium batteries, ACS Appl. Energy Mater. 3 (2020) 9264–9270.

[63] Z. Lu, F. Ciucci, Metal borohydrides as electrolytes for solid-state Li, Na, Mg, and Ca batteries: a first-principles study, Chem. Mater. 29 (2017) 9308–9319.

[64] H. Dong, J. Li, J. Guo, F. Lai, F. Zhao, Y. Jiao, D.J.L. brett, T. Liu, G. He, I.P. Parkin, Insights on flexible zinc-ion batteries from lab research to commercialization, Adv. Mater. 33 (1–35) (2021), 2007548.

[65] S. Wang, R. Fang, Y. Li, Y. Liu, C. Xin, F.H. Richter, C.-.W. Nan, Interfacial challenges for all-solid-state batteries based on sulfide solid electrolytes, J. Materiom. 7 (2021) 209–218.

[66] Advanced Technologies for Industry – Product Watch Solid-state-lithium-ion-batteries for electric vehicles, Product Watch Report European Commission (2020) 1–43.

[67] L. Smith, T. Ibn-Mohammed, D. Astudillo, S. Brown, I.M. Reaney, S.C.L. Koh, The role of cycle life on the environmental impact of $Li_{6.4}$ La_3 $Zr_{1.4}$ $Ta_{0.6}$ O_{12} based solid-state batteries, Adv. Sustain. Syst. 5 (2) (2021), 2000241, 1-12.

[68] W.D. Richards, L.J. Miara, Y. Wang, J.C. Kim, G. Ceder, Interface stability in solid-state batteries, Chem. Mater. 28 (2016) 266–273.

[69] T. Famprikis, P. Canepa, J.A. Dawson, M.S. Islam, C. Masquelier, Fundamentals of inorganic solid-state electrolytes for batteries, Nat. Mater. 18 (2019) 1278–1291.

[70] L. Han, M.L. Lehmann, J. Zhu, T. Liu, Z. Zhou, C.Heish X.Tang, A.P. Sokolov, X.C. Chen P.Cao, T. Saito, Recent developments and challenges in hybrid solid electrolytes for lithium-ion batteries, Front. Energy Res. 8 (1–19) (2020) 202.

[71] ISO, ISO Norm 14040:2006: Life Cycle Assessment: Principles and Framework, a, International Standard, Geneve, Switzerland, 2006.

[72] ISO, ISO Norm 14044:2006: Life Cycle Assessment: Requirements and Guidelines, b, International Standard, Geneve, Switzerland, 2006.

[73] S. Troy, A. Schreiber, T. Reppert, Gehrke H-G, M. Finsterbusch, S. Uhlenbruck, P. Stnzel, Life Cycle Assessment and resource analysis of all-solid-state batteries, Appl. Energy 169 (2016) 757–767.

[74] L. Vandepaer, J. Cloutier, B. Amor, Environmental impacts of lithium metal polymer and lithium-ion stationary batteries, Renew. Sustain. Energy Rev. 78 (2017) 46–60.

[75] C.M. Lastoskie, Q. Dai, Comparative life cycle assessment of laminated and vacuum vapor-deposited thin film solid-state batteries, J. Clean. Prod. 91 (2015) 158–169.

[76] J. Zhang, X. Ke, Y. Gu, F. Wang, D. Zheng, K. Shen, C. Yuan, Cradle-to-gate life cycle assessment of all-solid-state lithium-ion batteries for sustainable design and manufacturing, Int. J. Life Cycle Assess. 27 (2022) 227–237.

[77] A. Larrabide, I. Rey, E. Lizundia, Environmental impact assessment of solid polymer electrolytes for solid-state lithium batteries, Adv. Energy Sustain. Res. 3 (10) (2022), 2200079, 1-10.

[78] J.L. Schaefer, Y. Lu, S.S. Moganty, P. Agarwal, N. Jayaprakash, L.A. Archer, Electrolytes for high-energy lithium batteries, Appl. Nanosci. 2 (2012) 91–109.

[79] P.A. Nelson, S. Ahmed, K.G. Gallagher, D.W. Dees, Modeling the performance and cost of lithium-ion batteries for electric-drive vehicles, Third Edition. United States (2019), https://doi.org/10.2172/150328.

[80] T.A. Yersak, H.A. Macpherson, S.C. Kim, V.-.D. Le, C.S. Kang, S.-.B. Son, Y.-.H. Kim, J.E. Trevey, K.H. Oh, C. Stoldt, S.-.H. Lee, Solid state enabled reversible four electron storage, Adv. Energy Mater. 3 (2013) 120–127.

[81] F. Du, N. Zhao, Y. Li, C. Chen, Z. Liu, X. Guo, All solid state lithium batteries based on lamellar garnet-type ceramic electrolytes, J. Power Sources 300 (2015) 24–28.

[82] Y. Li, Z. Wang, C. Li, Y. Cao, X. Guo, Densification and ionic-conduction improvement of lithium garnet solid electrolytes by flowing oxygen sintering, J. Power Sources 248 (2014) 642–646.

[83] D.-.R. Shi, J. Fu, Z. Shadike, M.-.H. Cao, W.-.W. Wang, Z.-.W. Fu, All-solid-state rechargeable lithium metal battery with a Prussian blue cathode prepared by a nonvacuum coating technology, ACS Omega 3 (2018) 7648–7654.

[84] J.-.Y. Choi, D.J. Lee, Y.M. Lee, Y.-.G. Lee, K.M. Kim, J.-.K. Park, K.Y. Cho, Silicon nanofibrils on a flexible current collector for bendable lithium-ion battery anodes, Adv. Funct. Mater. 23 (2013) 2108–2114.

[85] T. Yoshinari, R. Koerver, P. Hofmann, Y. Uchimoto, W.G. Zeier, J. Janek, IInterfacial stability of phosphate-NASICON solid electrolytes in NiRich NCM cathode-based solid-state batteries, ACS Appl. Mater. Interfaces 11 (2019) 23244–23253.

[86] J. Liu, T. Liu, Y. Pu, M. Guan, Z. Tang, F. Ding, Z. Xuc Y. Li, Facile synthesis of NASICON-type $Li_{1.3}Al_{0.3}Ti_{1.7}(PO_4)_3$ solid electrolyte and its application for enhanced cyclic performance in lithium-ion batteries through the introduction of an artificial Li3PO4 SEI layer, RSC Adv. 7 (2017) 46545–46552.

[87] B. Key, D.J. Schroeder, B.J. Ingram, J.T. Vaughey, Solution-based synthesis and characterization of lithium-ion conducting phosphate ceramics for lithium metal batteries, Chem. Mater. 24 (2012) 287–293.

[88] M. Erakca, M. Baumann, W. Bauer, L. Biasi, J. Hofmann, B. Bold, M. Weil, Energy flow analysis of laboratory scale lithium-ion battery cell production, IScience 24 (1–32) (2021), 102437.

[89] Y. Deng, et al., Life cycle assessment of lithium sulfur battery for electric vehicles, J. Pow. Sour. 343 (2017) 284–295.

[90] R. Sacchi, C. Bauer, B.L. Cox, Does size matter? The influence of size, load factor, range autonomy, and application type on the life cycle assessment of current and future medium- and heavy-duty vehicles, Environ. Sci. Technol. 55 (2021) 5224–5235.

[91] C.T. Montenegro, J.F. Peters, M. Baumann, Z. Zhao-Karger, C. Wolter, M. Weil, Environmental assessment of a new generation battery: the magnesium-sulfur system, J. Energy Storage 35 (2021), 102053.