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Lithium-Sulfur Batteries: Current Status, Challenges and Path to Commercialization

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Abstract- Lithium-Sulfur (Li-S) batteries are now among the most promising coming-age energy storage solutions due to their remarkable theoretical energy density. Additionally, Sulfur is an abundant and low-cost material, making Li-S batteries a sustainable alternative to current energy storage technologies in both economic and environmental perspectives. These attributes make Li-S batteries a solid contestant for for a variety of applications, such as large-scale renewable energy storage, aerospace systems, and electric vehicles (EVs), where high energy density and lightweight design are highly required properties. However, despite these benefits, the practical commercialization of Li-S batteries is stalled by several challenges like polysulfide shuttle effect, lithium dendrite formation and poor conductivity of Sulfur compounds, which affect their electrochemical stability and cycle life negatively. In recent years, considerable progress has been made to address these limitations through research developments in cathode engineering, electrolyte designing, and anode protection strategies. The advancement in developing nanostructured Sulfur composite cathodes such as Sulfur-Carbon composites and Sulfur hosting porous materials has been a key to overcome Sulfur's low electrical conductivity problem. Several electrolyte formulations have been explored by researchers to supress Polysulfide Shuttle including solid-state electrolytes and concentrated Lithium salts. Moreover, Lithium alloys and protective electrode coatings have been examined to limit Lithium dendrite formation and increase battery life. In addition to that, practical considerations such as scalable manufacturing processes, cost-effective materials, and integration with existing battery infrastructure are crucial for its commercialization. In this review paper, we have investigated the present condition of Li-S battery infrastructure, the challenges being faced and the ongoing optimizations and innovations. This study sheds light on all the aspects central to its transition from laboratory prototypes to commercially viable technologies.

Keywords— Li-S batteries, Polysulfide shuttle, Dendrite formation, Solid-state electrolyte, Energy storage

1. INTRODUCTION

High-performance and sustainable energy storage solutions are critically needed today as a result of several global trends. Improved battery infrastructure is required due to rapid adoption of electric vehicles (EVs), demand of lighter and highly energy-dense batteries for space missions and inherent intermittency of renewable energy sources. Traditional energy storage systems have been unable to provide a solution to all of these issues. Furthermore, conventional energy storage systems like Lithium-ion batteries depend upon naturally scarce materials such as Cobalt and Nickel. The high-cost, complexity and environmental concerns associated with mining and processing of these materials make the demand for advanced energy storage technologies more pressing.

Lithium-Sulfur batteries appear as a promising candidate to replace these traditional battery technologies. Sulfur is abundantly available as it is a byproduct of several petrochemical refinery processes. It is a low-cost, less energy-intense and environment friendly substitute to conventional battery materials. Besides, lower weight and high energy density of Sulfur allows for superior transportation and designing efficiency which is crucial for Electric vehicle and aerospace usage. Owing to these attributes, Lithium-Sulfur batteries can address evolving global challenges and revolutionize the energy storage sector [1–5].

Despite all the advantages, Li-S batteries have not been as commercially successful as expected because it faces various technical and practical challenges mainly related to its chemical stability and cycle life. One of the most significant blocks for commercialization of Li-S batteries is their reduced lifespan compared to Li-ion batteries. This rapid capacity degradation is primarily due to a unique problem in Li-S batteries called 'Polysulfide Shuttle Effect'. This effect is caused by formation of soluble Lithium Polysulfides (Li_2S_6, Li_2S_8) during charge-discharge cycle. Dissolution of these polysulfides in electrolyte causes irreversible electrode material loss and chemical side reactions which lead to self-discharge, low coulombic efficiency and reduced overall battery performance [6–8]. An additional problem resulting from undesirable reactions in Li-S batteries is Lithium dendrite formation. Other challenges

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involve insulating nature of Sulfur, volume expansion during conversion between Sulfur and Lithium-Sulfur compounds and safety hazards [9–11]. All of these concerns must be addressed for Li-S batteries to develop as a viable alternative to Li-ion batteries. If these issues are eliminated, Li-S batteries would transform electric vehicle, renewable energy storage and aerospace applications.

In order to address the issues regarding less cyclic stability and inferior performance of Li-S batteries, researchers are applying different strategies such as novel electrolytes, integrated Carbon-based conductive frameworks and alternative anode compositions [12–14]. Jo et al. assembled high Sulfur loading Carbon nanotube cathodes for flexible high energy-density Li-S batteries to immobilize polysulfides via multimodal capturing effects [15]. Mariam et al. used aligned Carbon nanotubes (CNTs) to develop binder free Sulfur cathodes, delivering high conductivity and short ion-transport pathways [16]. Qu et al. designed an electrolyte containing a novel boron-based salt, lithium- perfluoropinacolatoborate (LiFPB), for long-cycling Li-S batteries [17]. This approach increased resistance to Lithium metal reduction and promoted the reinforcement of Solid electrolyte interphase (SEI), which resulted in improved lithium metal compatibility, high coulombic efficiency and superior capacity retention in Li-S pouch cells. These strategies aim to improve the Sulfur utilization, get over the low electrical conductivity problem of Sulfur and mitigate obstacles such as polysulfide shuttle and Lithium dendrite formation [18,19].

In addition to refinement of battery chemistry, scaling production to industrial levels poses another barrier to commercialization of Li-S batteries. Present battery production infrastructure is optimized for Li-ion batteries and specifically for Nickel, Cobalt and Manganese (NCM) cathodes, but Li-S battery production requires different materials and manufacturing processes. Various global companies are spending on large-scale production units to bring Li-S batteries to market. However, developing production infrastructure from ground level for a novel battery system requires heavy financial investments and time for setup. Therefore, many companies are focusing on modification of existing Li-ion battery production lines to accommodate Li-S battery production. Furthermore, the regulatory bodies aim at resolving safety issues relating to lithium metal batteries, enhancing the sustainability of the supply chain through minimizing the use of rare components, and meeting.

In this review, all the main advantages of the lithium-Sulfur battery system are considered, while the major problems that impede commercial deployment of this technology are analysed critically. Along with presenting the challenges, this review focuses on different solutions that have been proposed in order to solve the problems, such as the development of novel cathode materials, separators, electrolytes, and lithium metal anodes. The focus is on innovative methods in designing materials and engineering the electrodes in order to overcome the limitations imposed by low practical energy density and poor durability of lithium-Sulfur systems. In addition, this work provides an analysis of the recent approaches towards the commercialization of Li-S batteries. Finally, the conclusion of this review and future perspective for Li-S battery systems has been provided.

II. Advantages of Li-S batteries

A. High Energy Density

The theoretical energy density per kilogram of lithium-Sulfur batteries equals approximately 2600 Wh/kg while that of conventional Li-ion batteries ranges from 150 to 250 Wh/kg. Lead-acid batteries, for example, can provide energy densities of 30 to 50 Wh/kg. Thus, this battery type can prove especially effective in high-energy applications such as electric transport and aerospace. The theoretical high energy density of Li-S batteries can be explained by several important characteristics; one of them is the electrochemical reaction of lithium metal with Sulfur. During discharging, lithium ions move towards the cathode and Sulfur reduces to Li_2S via a multi-step process, producing great amounts of energy. Sulfur also has an exceptionally low molecular weight (about 32 g/mol), very high theoretical capacity (1675 mAh/g) relative to other cathode materials such as Cobalt Oxide. As opposed to the regular metal oxide cathodes that are used in Lithium-Ion batteries, Sulfur can be subjected to multiple reductions when charging a battery leading to high energy produced per mole of Sulfur. The other difference is that the Sulfur electrode can take part in redox reactions where a transfer of several electrons can take place per Sulfur molecule, thus increasing the energy output. This is contrary to lithium-ion batteries where a transfer of only one electron can happen.

B. Cost-effectiveness

Cost-effectiveness of Sulfur has become one of the reasons behind the popularity of this energy technology. Sulfur is one of the most widespread elements on Earth. Sulfur is a by-product of a number of industrial processes, including petroleum refining and natural gas extraction. It is available on an industrial scale and is produced in excess of 70 million tons per year. Therefore, the cost of Sulfur acquisition is relatively low, costing $100-$200 per ton on average, relative to other raw

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materials for battery manufacturing such as cobalt and nickel ($20,000-$60,000 per ton), which are costly because of their rarity, complexities in mining, and geopolitical risks. Although Sulfur itself is plentiful and affordable, there are still other factors which influence the final cost of lithium-Sulfur batteries, including processing and system costs. With researchers developing new ways to improve Sulfur cathodes, stabilize polysulfides, increase battery cycle life and use fewer expensive additives, the production cost of lithium-Sulfur batteries may be reduced even further. In the context of practical applications like EVs and power grid storage systems, the potential cost-effectiveness of lithium Sulfur cells could prove to be a major advantage.

C. Environmental Considerations and Sustainability

The safety of Sulfur makes these batteries safer to use while also increasing their sustainability, as Sulfur is both safe and plentiful. Sulfur is one of the materials considered environmentally-friendly and having multiple sustainability benefits. In fact, one of the major sources of Sulfur that is needed to create batteries is the waste products of the respective industries such as the petroleum refining industry. As a result, Sulfur can be reused as it becomes waste products that can be harmful to the environment in the process. It is also worth noting that Sulfur is less toxic than cobalt, a common element in other types of batteries, the extraction of which has been criticized because of the practices involved, especially in the Democratic Republic of Congo.

III. Challenges in Li-S Batteries

Although they have enormous potential, there are some problems that limit the commercial utilization of lithium-Sulfur batteries. These issues must be resolved to improve Li-S battery technology for its practical use.

A. Polysulfide Shuttle Effect

One of the key problems that affect Li-S batteries is the process known as polysulfide shuttle. Polysulfides are very soluble in organic electrolytes, which makes up the heart of the polysulfide shuttle. It causes them to dissolve in the electrolyte and diffuse from the Sulfur cathode to the lithium anode. The polysulfide shuttle plays a key role in the limiting the practicality of the Li-S batteries, having an adverse effect on cyclic stability and overall battery performance.

1) Mechanism of Polysulfide Shuttle Effect: The working of a Li-S battery involves various chemical reactions of Sulfur while charging and discharging. During discharge, Sulfur from the cathode and lithium ions from anode react to form lithium polysulfides such as Li_2S_6, Li_2S_4, and Li_2S_2. The lithium polysulfides are just intermediate compounds in the electrochemical reaction and not involved in the formation of lithium sulfide (Li_2S). Although lithium polysulfides could be involved in a reversible electrochemical reaction, it poses great difficulties due to its high solubility in the electrolyte. As a result, the polysulfides do not stay confined to the cathode anymore and move freely in the electrolyte. This process is termed as polysulfide shuttle phenomenon [20,21].

Once the polysulfides dissolve into the electrolyte solution, they are able to migrate towards the anode through the influence of electrochemical potential gradient. When these polysulfides migrate to the anode, they participate in some unwanted reactions that are not be useful in terms of charging/discharging processes. Rather, the polysulfide participation in these reactions will result in loss of active materials and reduced performance of the battery. Another effect that results from the migration of the polysulfides is their deposition on the anode surface. This could lead to the creation of a solid electrolyte interface layer, resulting in higher resistance of the cell and reduction of cell capacity. In the worst-case scenario, the polysulfide accumulation in the anode will cause overcharge or overdischarge of the battery.

2) Consequences of Polysulfide Effect: These polysulfides become redundant to the electrochemical process after their dissolution in the electrolyte. Some of these polysulfides can eventually be returned to the cathode and participate in the reaction, while others are not completely reduced and precipitate as insoluble lithium sulfide (Li_2S) on the surface of the electrode. This irreversible consumption of active material decreases the total capacity of the battery. Essentially, the battery's capacity to provide charge decreases since some of the Sulfur is no longer cycled. This results in loss of active material and hence loss of capacity of the battery with time.

Polysulfides migrating from anode to cathode also cause unwanted reactions that damage the electrode structure within the battery. Frequent dissolution and migration of polysulfides throughout several charge and discharge cycles weaken the cathode and cause premature wear of the battery [21,22].

The polysulfide shuttle phenomenon enhances the internal resistance of the battery. Since polysulfides continuously shuttle between the cathode and anode, they also become part of the formation of the layer of resistivity on the electrodes that inhibits the flow of ions and electrons in the batteries. This raises internal resistance, which lowers the efficiency and output of the battery. Internal resistance also further exacerbates capacity loss and the performance of the battery in terms of power delivery.

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Furthermore, polysulfides shuttled to the anode and oxidized could cause self-discharge, even when the battery is idle. Thus, this unwanted reaction causes additional capacity loss in scenarios where the battery needs long periods of rest. Moreover, due to shuttling of polysulfides from the cathode, they react with the electrolyte and generate unfavourable products, thereby deteriorating its efficiency in charge transportation.

3) Factors Contributing to Polysulfide Migration: The solvent composition of the electrolyte governs the solubility behaviour of polysulfides and, therefore, the capability of the compounds to dissolve and shuttle across the battery. The electrolyte used in lithium-ion batteries is made from organic solvents, including ethylene carbonate (EC), propylene carbonate (PC) and diethyl carbonate (DEC). Such electrolyte solvents are heavily applied in Li-S batteries as well. However, they show varying degrees of solvation power and polarity, affecting the interaction of polysulfides with the electrolyte. Due to high polarity, DMSO and DOL are effective solvents in dissolving polysulfides. As a result, polysulfides become more mobile and capable of migrating from the Sulfur cathode towards the lithium anode and causing the shuttle effect. Other types of solvents, namely, non-polar tetrahydrofuran (THF), demonstrate low levels of polysulfides solubility and, thus, limit the diffusion of polysulfides. At the same time, the use of such solvents might be detrimental due to low ionic conductivity and low electrochemical stability. The choice of lithium salts for use in the electrolyte may greatly affect the rate at which polysulfides dissolve and migrate. While $LiPF_6$ (lithium hexafluorophosphate) is extensively used in lithium-ion batteries, it is not suitable for use in Li-S batteries as it has been shown to increase the polysulfide shuttling. LiTFSI (lithium bis(trifluoromethanesulfonyl)imide) exhibits enhanced stability and less aggressive nature towards polysulfides. However, it has lower lithium-ion solvation ability than $LiPF_6$, and it may, therefore, affect the conductivity of the electrolyte.

In addition, the conductivity of the electrolyte becomes essential for ensuring effective lithium ions transfer through the medium. Although the high electrolyte conductivity is preferred in terms of increasing the speed and efficiency of battery operation, it can also promote polysulfides dissolution and migration. Consequently, both viscosity and conductivity of the electrolyte must be carefully balanced to improve battery characteristics while preventing polysulfides dissolution.

The structure of the Sulfur cathode is also important in determining the trapping, conversion, and transportation of lithium polysulfides. Conventional Sulfur electrodes suffer from volumetric changes too which cause mechanical damage leading to detachment from the current collector, thus limiting cycle life. High porosity increases ion diffusion and electrolyte permeation into the pores of an electrode. This improves electrolyte ion mobility and facilitates faster reaction rates. It also ensures continuous conductive pathways for electrons resulting in fast redox reactions and Sulfur conversion. Interconnected porosity helps reduce charge transfer resistance and even Sulfur deposition on electrodes. As a result, there will be no formation of non-conducting lithium polysulfide. Nevertheless, the high porosity may also promote the dissolution of lithium polysulfides leading to shuttling effects. Modification of the electrode-electrolyte interface through the use of surface coatings/functionalization also helps limit polysulfide diffusion. Some metal oxides (TiO_2, MnO_2), as well as metal sulfides (CoS_2, MoS_2), show high affinity for polysulfides and suppress their migration. In addition, they catalyse the reduction of polysulfides and help return them back to active Sulfur forms. The use of three-dimensional electrodes, including nanostructured materials and hybrid structures, is useful in increasing the loading of Sulfur and providing better confinement of polysulphides. Electrodes with conductive architectures using carbon nanotubes, graphene aerogels, and MOFs ensure easy flow of electrons, hence reducing the resistance to charge transfer [23].

Charge-discharge rate also has an effect on polysulfide formation and their dissolution in the electrolyte. The use of high charge-discharge rates (C-rate) increases the speed of electrochemical reactions; as a result, Sulfur is partially transformed into polysulfides, while a significant portion of polysulfides dissolves into the electrolyte. Lower C-rates helps in reducing the shuttle effect, but extremely low C-rates may cause passivation of the electrode surfac. The selection of the optimal C-rate allows maximizing the efficiency of Li-S batteries. Additionally, increased temperature accelerates the reaction and utilization of Sulfur. However, it favours the dissolution of polysulfides and increases the shuttle effect. At low temperature, the movement of lithium ions becomes slower, and the transformation of polysulfides is reduced.

B. Low Electrical Conductivity

Low electrical conductivity is one of the critical barriers to the industrialization of Lithium Sulfur batteries. The active cathode material, i.e., Sulfur and the discharge products, such as lithium sulfide (Li_2S), are both poor conductors of electricity and ionic charge carriers, resulting in poor reaction kinetics, reduced efficiency, and increased internal resistance. Its wide energy gap of 2.7 eV does not permit easy passage of electrons, thus hindering the conduction of electricity. Moreover,

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elemental Sulfur appears as a molecule, wherein the atoms are tightly held by strong covalent bonds. This insulating nature of Sulfur results in huge overpotentials, decreasing the battery efficiency. In addition, there is a significant amount of Sulfur that remains unreactive because of the lack of proper electrical contact with the current collector and conductive material. The poor electrical contact of the active material with the current collector increases interface resistance.

Discharge products such as lithium sulfide and lithium polysulfides also have high resistance to conductivity. Like Sulfur, lithium sulfide Li_2S has high energy gaps (3.6 – 3.9 eV). Hence, they do not facilitate efficient electrical transport. Also, the electronic conductivity of Li_2S is very low (~ 10-14 S/cm at room temperature) hence affecting the rate of redox reaction when the redox reaction takes place. Unlike typical lithium-ion battery cathodes, the lithium diffusion coefficient of Li_2S is lower making it less electrochemically active. As a result, more energy is needed for the occurrence of the charge and discharge reactions, making the system energy inefficient.

C. Sulfur Cathode Volume Expansion

Pristine Sulfur appears in the form of orthorhombic S_8, which has a density of 2.07 g/cm³. Lithium ions (Li^+) combine with S_8 to finally produce Li_2S. The density of Li_2S (1.66 g/cm³) is much smaller than that of Sulfur (2.07 g/cm³), causing an increase in volume by about 80%. Moreover, the enlargement of the Sulfur cathode is not limited to the inherent volumetric characteristics of the S_8 and Li_2S compounds, but it is rather determined by the processes taking place at the cycle level. Usually, Sulfur cathodes consist of porous carbon or polymer materials as a host for Sulfur. When Li_2S precipitation occurs, it fills all the pores inside the cathode material. The precipitated solid-phase Li_2S takes more space compared to the initial Sulfur particles, which makes the electrode thicker [24,25].

The enlargement of the Sulfur cathode leads to continuous changes in electrochemical and mechanical stress factors, which appear and evolve through many cycles. The lithiation of Sulfur causes an expansion process that creates compressive stresses within the electrode material. The contraction of Sulfur in the case of de-lithiation (charging) causes tensile stresses in the electrode. The repetitive stress and pressure created by the contraction and expansion processes could cause the breakdown or displacement of the conductive material used as a support for the reaction process. Sulfur is brittle in nature and therefore prone to breaking when compared to flexible electrode materials. The formation of cracks causes the entry of electrolytes within them and consequently increases the rate of pulverization and the release of polysulfides. Detached pieces of the cathode reduce electronic conduction.

The swelling of the Sulfur cathode causes various undesirable effects in the separator too. With the swelling of the cathode during the process of discharging, it pushes outwards the separator, which results in wrinkles and/or buckling in the separator over many cycles. This phenomenon causes unequal flow of ions and creates zones of high resistance. The phenomenon also leads to compaction and pore clogging in the separator that causes obstruction in the diffusion of lithium ions through it. As the separators experience cyclic expansion and contraction, they develop local folding or crumpling, leading to variations in their thickness and resulting in the collapse of the porous nature of the separator.

D. Lithium Dendrite Formation

The anode made of lithium metal expands because of the constant deposition and stripping of the lithium ions during cycling. During charging, ideally, lithium ions should uniformly deposit on the lithium metal surface, giving a smooth and compact layer. In reality, however, there is some inhomogeneity in current density, which leads to some non-uniformity in ion flux and lithium surface roughness, so the lithium deposits preferentially at certain points of contact, forming needle-like or mossy lithium structures called dendrites. As the cycle repeats, dendrites grow, developing in the direction away from the lithium surface [26–28].

This phenomenon causes the anode to require more lithium and expand its volume. Because of their branched structure and porous character, dendrites form voids inside, adding to the already significant anode volume changes. Increased currents accelerate the rate of nucleation of lithium on the electrode surface and increase the probability of non-uniform deposition forming dendrites instead of smooth layers. Increased non-uniformity of ion flux also increases the number of lithium protrusions, thus promoting anode swelling. Lithium surface roughness plays a significant role in its deposition [29–31].

Another reason for volumetric expansion of lithium anode is the formation of solid electrolyte interphase (SEI) between lithium anode and electrolyte. In subsequent charge-discharge cycles, the SEI layer continuously breaks down and reforms owing to mechanical forces exerted during the process and lithium dissolution/deposition. More reaction sites for decomposition of the electrolyte occur with each new cycle, thus causing SEI to get thicker continuously. The continuous SEI growth means the loss of lithium metal and an increase in interface resistance. The process of SEI formation and decomposition creates mechanical stress on the anode surface.

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As such, since SEI itself is neither a uniform nor perfectly elastic layer, its continuous production and rupture lead to local expansion of lithium metal.

The volume changes may result in delamination of the lithium film from the copper current collector causing increased resistance and accelerated capacity fading. In addition to affecting the active material layer, mechanical stresses also affect the aluminium current collector. Ultimately, the stresses may be too high to induce current collector deformation and delamination from the active electrode, resulting in a marked increase in cell resistance. The distortion of the separator, especially its thinning, gives ways for the growth of lithium dendrites that ultimately cause the penetration of the separator by the dendrites. This leads to permanent short circuit, which causes quick discharge and heat generation, thus increasing the chance of thermal runaway, which may lead to catastrophic failures such as fires. The compression in regions where the separator experiences volume swelling greatly reduces the porosity, resulting in electrolyte exhaustion in some regions and hence uneven plating of lithium [32–34].

IV. Recent advancements in the field

A. Enhanced Cathode Materials

1) Porous Carbon Structure: Porous S–C composites are mainly designed for the improvement of sulphur utilisation, electrical conductivity and polysulphide shuttle effect. To this end, a conductive carbon matrix with tunable porosity is developed to effectively encapsulate the sulphur and to accommodate the volume expansion during cycling. An ideal porous structure facilitates the efficient electron transport and the physical confinement of sulphur species to reduce the polysulphide dissolution into the electrolyte [35–37]. Sultanov et al. synthesized porous Carbon with high specific surface area from rice husk through Carbonization and activation, which was later utilized as a porous matrix for Sulfur cathode via melt-diffusion technique [38].

2) Heteroatom Doping: Heteroatom doping (e.g., with nitrogen) of carbon materials can add free carriers, thereby increasing the electrical conductivity. This enhancement allows improved electron transport in the cathode which is essential for the redox reactions of sulphur species. Heteroatom doped carbons can interact strongly with lithium polysulfides and anchor polysulfides, alleviating the shuttle effect. For example, nitrogen-doped carbon materials have exhibited a strong affinity to sulphur species, which mitigates the polysulphide dissolution and improves cycling stability. Some heteroatoms may also lend catalytic properties to the carbon host in order to accelerate the conversion kinetics of sulphur species [39,40]. Li et al. used discarded corrugated paper and thiourea as carbon and dopant sources to create a carbon membrane co-doped with sulphur and nitrogen. This membrane promotes quick redox conversion while providing polysulfides with both strong chemical anchoring and physical confinement [41]. Using ramie waste glue, they created a range of cobalt-nitrogen co-doped porous carbon materials (Co,N-C) that efficiently adsorb lithium polysulfides, significantly lowering the shuttle effect and enhancing conversion kinetics with a small degradation rate of 0.11% per cycle [42].

3) Hybrid composites: The synergistic combination of conductive, polar and catalytic materials has rapidly developed hybrid composite cathodes that address the limitations of sulphur. Recent architectures are advanced material engineering strategies for the multi-functional design to boost the performance of Li-S batteries [43].

Graphene-TiO_2 Hybrid Composite system combines the mechanical flexibility and superior electrical conductivity of graphene with the polysulfide-trapping ability of TiO_2. TiO_2 nanoparticles are often deposited or anchored on graphene sheets to form a composite matrix that can simultaneously enhance electronic transport and suppress polysulphide migration., Li et al. used filtering to create an ultralight TiO_2-graphene (TiO_2-G) layer with a sandwich structure on the separator's surface to trap polysulfides and prevent its diffusion. The TiO_2-G layer enhances the sulphur electrode's capacity retention rate to 69.2% from 18.6% and raises its specific capacity from 715 to 991.7 mAh/g [44].

The CNTs are covered by MoS_2 to generate conductive matrix referred to as S/CNT-MoS_2 composite system . MoS_2 is a transition metal dichalcogenide possessing layered structure. It displays excellent catalytic properties that are favourable for polysulfide adsorption and conversion. Another type of hybrid material involves the use of dual-function matrix created through combination of porous Carbon and MnO_2, with Carbon providing suitable environment for Sulfur retention and resistance. In order to create an HPCs/S@MnO_2 composite for enhanced lithium-Sulfur batteries, Dai et al. described the in-situ development of δ-MnO_2 nanosheets onto hierarchical porous carbon microspheres (HPCs). High sulphur loading and efficient confinement of LiPSs are possible with the carefully crafted hybrid architecture [45].

Titanium nitride (TiN) is a highly conductive polar material embedded in a carbon matrix for hybrid cathode design. It has better conductivity than many metal oxides and chemically adsorbs polysulfides. It facilitates fast redox conversion through catalysis, and reduces charge transfer resistance and

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loss of polysulfides. Ren et al. created a unique S@TiN/MC-CNT composite in which sulphur was embedded with TiN and multi-walled carbon nanotubes (MC-CNT). Through its surface-active sites, the TiN component allowed polysulfides to be chemically anchored, reducing losses from polysulphide dissolution. In the meantime, sulphur volume expansion was successfully accommodated by the stable three-dimensional conductive network that MC-CNT offered [46].

4) Inverse Vulcanisation: The use of inverse vulcanization has turned out to be groundbreaking technology in the formation of Sulfur cathodes for lithium-Sulfur (Li-S) batteries. Inverse vulcanization is the polymerization of elemental Sulfur with organic cross-linkers and produces polymers that contain Sulfur at high concentration and resolve most limitations associated with conventional Sulfur cathodes. Inverse vulcanization entails melting elemental Sulfur beyond its melting point, producing Sulfur radicals, which react with unsaturated organic compounds (dienes) and produce Sulfur-containing polymers [47–50]. Huang et al. created an inverse vulcanised polymer (IVP) that was integrated into the cathode of Li-S batteries and contained a specially created quaternary ammonium salt called poly(S-r-TAEAB). This reduced the dissolution of lithium polysulphide by covalently attaching sulphur atoms to the carbon framework [51]. Tominaga et al. developed a lithium-Sulfur battery system using chemically altered thermoplastic sulphur polymers as cathode active materials. The resultant resins with a high sulphur content demonstrated adhesiveness, extensibility, and self-healing qualities [52].

B. Modified Electrolyte Structure

Ether-based liquid electrolytes have been the traditional choice for lithium-Sulfur batteries because they can effectively dissolve sulphur species and lithium salts and have good ionic conductivity at ambient temperatures. The general solvent system is a mixture of 1,2-dimethoxyethane (DME) and 1,3-dioxolane (DOL) with lithium bis(trifluoromethanesulfonyl)imide (LiTFSI) as the conducting salt and lithium nitrate ($LiNO_3$) as an additive.

The solvents, DME and DOL, have lower viscosity and polarity that allow for fast movement of lithium ions, thus allowing for fast rates of charge/discharge. Furthermore, these two solvents dissolve Sulfur elements and lithium polysulfide, allowing for maximum use of the active material. Use of lithium nitrate in the system ensures formation of a stable and protective solid electrolyte interface (SEI) layer in the lithium metal electrode. This prevents any unwanted reactions between the dissolved polysulfides and the lithium electrode, thus preventing any short-circuits from occurring.

Conventional ether-based electrolytes have their benefits, but also critical drawbacks that limit long-term and high-performance operation. Lithium polysulfides (Li_2S_6-Li_2S_8) are highly soluble in ether-based solvent. Ether solvents such as DME and DOL are volatile and flammable and present serious safety concerns for large scale or automotive applications. Additionally, these solvents break down at potentials > 4V vs. Li/Li +, thus limiting the cell's upper voltage limit and its compatibility with high-voltage cathodes. Although $LiNO_3$ is beneficial for SEI formation, it is consumed during cycling and may dissolve over time, which may lead to unstable lithium plating and dendrite formation in long-term operation.

1) High-concentration electrolyte (HCLEs): High-Concentration Electrolytes Also called "concentrated electrolytes" or "solvent-in-salt electrolytes". Formulations in which the salt-to-solvent ratio is much higher than in conventional electrolytes. In a typical Li-S battery, standard electrolytes contain 1M salt concentration, while HCEs may go beyond 3M, sometimes reaching saturation.

These electrolytes possess fewer free solvent molecules and enhanced ion-pairing/aggregate formation, different solvation structures and improved electrochemical and thermal stability. Such high concentration results in the formation of strong SEI layers on the surface of lithium anodes. Such SEI layers are more inorganic in nature with a predominance of LiF, which acts to suppress the growth of dendrites and reduces parasitic reactions between polysulfide intermediates and thus promotes reversibility of Li deposition and stripping. The HCEs show better oxidative stability because of the lower number of available solvent species that can easily get oxidized. Thus, it increases the electrochemical window that allows the usage of high-voltage cathode materials.

But the HCEs, despite their advantages, also pose new challenges. The high salt concentration enhances the viscosity, which might hinder the ion transport and reduce the rate capability. The large amounts of salt (often LiTFSI or LiFSI) increase the cost of the electrolyte and limit large scale viability. Other HCEs are incompatible with conventional separators or binders due to modified chemical environments.

Localised High-Concentration Electrolytes (LHCEs) are a new class of electrolytes that aim to combine the electrochemical stability and polysulfide-suppressing ability of high concentration electrolytes (HCEs) with the low viscosity and cost-effectiveness of diluted conventional electrolytes. LHCEs are produced by introducing inert diluents (non-solvating co-solvents) to HCEs, in which the advantageous

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solvation structure is preserved without compromising the electrolyte performance. In a typical LHCE, only a fraction of solvent molecules interacts with lithium ions, resulting in a highly coordinated Li+ environment similar to that in HCEs.

The addition of diluents decreases viscosity and enhances ionic conductivity in comparison to pure HCEs. Moreover, the lower lithium salt content of LHCEs than HCEs is more economical for commercial applications. Hou et al. described a local high-concentration electrolyte for Li-S batteries that was made by mixing the traditional electrolyte with "diluent" 1,1,2,2-tetrafluoroethyl methyl ether (TME). This work protected the Li metal by limiting the cathode's "shuttle effect" and creating a stable SEI on the anode. Li-S batteries with higher capacity retention of 60% after 400 cycles at 0.5 C were obtained without any LiNO3 addition, and the average Coulombic efficiency of the Li anode reached 98.87% after 120 cycles [53]. Another example of LHCEs is Lithium bis(trifluoromethanesulfonyl)imide (LiTFSI) in 1:1 DOL/DME with 40% HFE (hydrofluoroether).

2) Solid-state electrolytes (SSEs): The shift from conventional electrolytes to solid state electrolytes is due to certain considerations associated with the safety, performance and designing of Li-S battery. First, conventional electrolytes are flammable organic solvents that can pose serious safety hazards in case of a thermal runaway reaction or a short circuit due to their combustibility. On the other hand, SSEs are not flammable, thereby lowering the probability of accidents such as battery fires or explosions.

Most importantly, the introduction of SSEs allows employing lithium metal electrodes as the source of energy instead of carbon electrodes, which could increase the theoretical energy capacity of a battery twice over. As mentioned before, this feature is extremely valuable in applications such as EVs since it could increase the range of operation of the device. Moreover, solid-state batteries are capable of operating at higher and lower temperatures as compared to conventional batteries, which widens the scope of their use. Furthermore, SSEs minimize the number of side reactions within the battery and eliminate any chances of lithium dendrites forming, which can cause short circuits in the battery and reduce its lifetime.

Inorganic solid electrolytes are ceramic-based materials, which possess high ionic conductivity and mechanical strength. Garnet-type electrolytes (e.g. $Li_7La_3Zr_2O_{12}$ or LLZO) have high ionic conductivity (~10-3 S/cm) and stability against lithium metal, but interface compatibility with sulphur and brittleness are concerns. Sulfide-based electrolytes (e.g. $Li_{10}GeP_2S_{12}$ or LGPS) offer good deformability and interfacial contact, but chemically unstable with moisture (produces H_2S gas). another example of inorganic solid electrolytes is NASICON-type electrolyte which show reasonable ionic conductivity and stability and are prone to reduction by lithium metal.

Polymeric electrolytes consist of a polymer matrix (usually polyethylene oxide, PEO) in which a lithium salt (e.g. LiTFSI) is dissolved. These materials conduct lithium ions by segmental motion of the polymer chains. The main advantages of polymeric electrolytes are enhanced safety owing to non-flammability, suppression of lithium dendrites owing to mechanical rigidity and inhibition of polysulphide diffusion. However, a challenge that needs to be solved is the low ionic conductivity of these electrolytes at room temperature (~10^{-6} to 10^{-8} S/cm).

Composite electrolytes are hybrid systems, which combine inorganic and polymeric components to balance conductivity, mechanical strength and interfacial stability. PEO + LLZO shows the higher ionic conductivity (~ 10^{-4} S/cm at 60 °C) and lower crystallinity of PEO, resulting in the enhanced lithium-ion transport and mechanical properties. The ceramic LLZO further provides physical blocking of polysulfides. In a work by Cheng et al., $Li_{6.28}La_3Al_{0.24}Zr_2O_{12}$ nanofiber (LLAZO NF) was used to strengthen a composite polymer electrolyte. This electrolyte had excellent ionic conductivity and contained a garnet nanofiber filler in a PEO-based polymer system. A high Li-ion transference number was achieved by the fast and continuous paths for lithium-ion conduction made possible by the well-connected organic–inorganic network [54].

Despite the promising performance, challenges still remain for room temperature ionic conductivity comparable to liquid electrolytes and the chemical compatibility of the composite electrolytes with high-capacity electrodes.

3) Functionalized Electrolytes or Additives: Functionalised electrolytes are realised by adding specific chemical additives or functional groups to the base electrolyte system to overcome the major challenges in lithium-Sulfur batteries, mainly polysulphide shuttle effect, poor lithium metal stability and low cycle life. Functionalised electrolytes are different from conventional electrolyte modifications (e.g., high concentration or solid-state systems) in that they change the chemistry at the molecular or interfacial level, often without significantly changing the bulk properties of the electrolyte.

Functional additives such as $LiNO_3$ or LiFSI decompose on the lithium surface to form a homogeneous and strong SEI layer. This layer prevents further attack by polysulfides and also prevents dendritic growth.

Some functional groups (e.g., amine, fluorinated, or sulfonated groups) can chemically interact with polysulfides

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and confine them close to the cathode. Additives like HMTA or ionic liquids with imidazolium rings can trap or complex with polysulfides, limiting their mobility. Highly polar molecules or viscosity tuned solvents can trap polysulfides in the inside of the cathode structure. Zhong et al. applied a single amino acid, L-leucine (Leu), at an extremely low dose of 0.1 wt%. This additive significantly improved the electrolyte's wettability on the separator and promoted Li+ ion transit. Additionally, it efficiently counteracted the shuttle effect by demonstrating a catalytic effect on the transformation of soluble Li_2S_x into solid Li_2S [55]. Jiang et al. used Tetrabutylammonium triiodide (TBAI 3), a new ionic liquid, as a multi-effect electrolyte addition to address the short life and low coulombic efficiency of Li-S batteries. In addition to forming a dynamic electrostatic shielding layer at the lithium protrusions and causing uniform lithium deposition, TBA+ cations coordinated with solvent molecules and lowered the desolvation barrier [56].

C. Anode Protection and Interface Engineering

Recently, great efforts have been devoted to the anode protection of Li-S batteries, including dendrite suppression, interfacial resistance reduction and solid electrolyte interface (SEI) stabilisation. This section emphasises the recent advances in interface engineering, especially protective coatings, SEI stabilisers and hybrid composite anodes.

1) Protective Coatings: Protective coatings for lithium anodes in lithium-Sulfur (Li-S) batteries are essential to suppress dendrite growth, reduce interfacial resistance and increase the overall cycling stability of the battery. Over the last few years, studies have focused on the design of multifunctional coatings for both electrochemical stabilisation and interface compatibility as well as mechanical protection [57,58].

Lithium-phosphorus oxynitride (LiPON) is a popular protective coating material, owing to its excellent chemical stability, ionic conductivity, and mechanical robustness. Wang et al. showed a solid electrolyte interface (SEI) film made of lithium phosphate (LiPON) that was applied on a lithium electrode using an electrodeposit technique. It was discovered that this type of film successfully prevented charge transfer at the electrode-solution interface, which resulted in a more stable interface impedance on the electrode and enhanced the interface contact with the electrolyte [59].

Polymer-ceramic composites have attracted much attention as protective coatings because of their mechanical flexibility, thermal stability and ionic conductivity. Lee et al. suggested creating a single-ion-conducting ceramic/polymer composite layer by adding Al-doped LLZO particles to a single-ion-conducting polymer (SICP) matrix created by copolymerising a styrene-lithium 4-styrenesulfonyl (trifluoromethanesulfonyl) imide monomer and poly(ethylene glycol) diacrylate. A thin 40 μm Li-metal electrode was able to cycle steadily at 5 mA cm^{-2}, with an areal capacity of 3 mAh cm^{-2} for 86 cycles in a Li symmetric cell thanks to the optimised LLZO/SICP protective layer. Furthermore, after 400 cycles at 4.5 mA cm^{-2} (≈3 C), full cells maintain 82% of their initial capacity [60].

Metal-based coatings, especially silver (Ag), zinc (Zn) and aluminium (Al) based ones, have been increasingly used as anode protection strategies due to their high conductivity and chemical compatibility.

Fluorinated coatings have been proposed as an effective way to stabilise the SEI layer and lower the interfacial impedance of Li-S batteries. Xu et al. used a straightforward and scalable fluorination technique to create a free-standing three-dimensional (3D) nickel nanowires (NiNWs) current collector coated with lithiophilic NiF_2 nanosheets (NiNWs@NiF_2). The lithiophilic surface of nanosheets lowered the Li nucleation barrier and enable homogeneous Li ion deposition, according to experimental study. Fast electron transport and reduced volume changes while cycling were made possible by the 3D conductive NiNWs network [61].

2) Artificial Layers and Interfacial Engineering: The artificial SEI (Solid Electrolyte Interphase) layers have drawn great interests as promising strategies to stabilise the lithium anode surface and solve the problems of dendrite growth and polysulphide shuttling. Recent advances in SEI engineering have been dedicated to the design of multifunctional layers with both ionic conductivity and mechanical protection. Song et al. developed an artificial SEI membrane for dendritic-free Lithium anode, using a chemically and physically reinforced membrane (C-Li@P) made of the biocompatible Li+ coordinated carboxymethyl guar gum (CMGG) and polyacrylamide (PAM) polymers. In addition to promoting uniform Li plating by directing ion flow along the fibre interspace, this membrane with hollow channels also created a favourable interface chemistry [62].

Zhao et al. demonstrated an artificial SEI layer of the Li metal anode, made of a polyurethane elastomer (TPU) with great flexibility and air stability. The TPU-modified Li symmetric battery was able to cycle steadily for 1300 hours at a current density of 1 mA/cm^2, as well as at a high current density of 10 mA/cm2. After 400 cycles, the improved Li/Cu half-cell's Coulomb efficiency remained at 97%. Furthermore, the $LiFePO_4$ cathode complete cell demonstrated exceptional long cycle stability, retaining 90% of its capacity after 1500 cycles at 5 C [63].

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3) Hybrid composite Anodes: Hybrid composite anodes combine conductive scaffolds, lithium hosts and electrolyte stabilisers, which can suppress dendrite growth and improve Li-ion kinetics in Li-S batteries. Recent studies suggested multifunctional hybrid anodes for simultaneously addressing the problems of mechanical stability, ionic conductivity, and dendrite suppression. Carbon-based hybrid anodes, including graphene, carbon nanotubes (CNTs), and porous carbon matrices, have shown remarkable enhancement in lithium-ion transport and dendrite suppression. Also, MOF based anodes have appeared to have tunable porosity, ionic conductivity and to regulate lithium-ion flux. Hybrid anodes employing alloys such as lithium-aluminium (Li-Al) and lithium-tin (Li-Sn) are also explored because of their high theoretical capacity and suppression of dendrites. In a study done by Pan et al., an all-solid-state LSB with a Li-Al alloy anode and a melting-coated S composite cathode operated steadily for more than 200 cycles, with a capacity retention of 93.29%. Additionally, 541 Wh kg^{-1} of specific energy was provided by a Li-S complete cell with a low negative-to-positive ratio of 1.125 [64]. Lithium-tin alloy anodes proposed by Dong et al. demonstrated a low potential platform (0.03 V vs. Li/Li^+) and an ultra-high lithium content (3282 mAh g^{-1}), ensuring high energy density. This resulted in high critical current density of 4 mA cm^{-2} and up to 1200 hours long lifespan. The fabricated batteries exhibited excellent room-temperature cycling stability, with a capacity retention rate of 97.8 % after 235 cycles [65].

V. Commercialization Approach

The scalable fabrication of the core components of lithium–Sulfur (Li-S) batteries, i.e., Sulfur cathode composites, lithium metal anode, electrolyte and separator, is a critical prerequisite for their successful commercialization. Although important advances have been achieved at the laboratory scale, the transition of these developments into industrially viable manufacturing processes requires careful optimization of synthesis routes to balance electrochemical performance, production cost, material availability and manufacturing throughput. It also needs to be compatible with existing lithium-ion battery manufacturing infrastructure to keep capital investment low. Getting this balance right is critical to unleashing the commercial potential of Li-S batteries in next-generation energy storage applications.

A. Pilot-scale Manufacturing and Case Studies

Several startups and companies have demonstrated pilot-scale and pre-commercial production of Li-S cells, validating many of the above processes. Lyten (USA) has adopted a particularly aggressive stance with its fully-automated pilot line consistently producing >90% good cells. Crucially, this line was built using standard lithium-ion manufacturing equipment: Lyten converted an existing Li-ion assembly line in just 6 weeks (at <2% additional capital cost). This demonstrates that Li-S cells (Sulfur cathodes and Li-metal anodes) can be manufactured on current pouch/cylindrical cell lines. Lyten is looking to scale up from its pilot in San Jose to a gigafactory in Reno. In April 2025, Lyten announced that it is producing battery-grade lithium-metal foil domestically, a key step toward vertical integration of the Li anode.

Sion Power (USA), known for its "Licerion®" Li-metal batteries, is setting up a large-format pilot line in Arizona. In early 2025 Sion announced a new fully-automated line capable of 75 MWh/year of 56 Ah Li-metal cells. This move transitions Sion from lab-scale coin cells to near-commercial format. Like Lyten, Sion's improvements (e.g. Li-metal anode lamination) are designed to be compatible with existing battery equipment. The company emphasizes that this step produces cells for applications including EVs and grid storage.

OXIS Energy (UK/Brazil) – now part of Britishvolt – had been developing Li-S cell factories in Wales and Brazil. Its plans illustrated that Li-S production lines (targeting specific energy >500 Wh/kg) are technically feasible with moderate ramp-up, and that Li-S cells can be built at scales approaching existing Li-ion plants.

Li-S Energy (Australia) is another pilot-scale example. In 2024 it commissioned a 2 MWh/year pouch-cell line in Geelong. Notably, it contains "the largest battery dry room in Australia," reflecting strict moisture control needed for Li-metal anode production. Li-S Energy aims to provide hundreds to thousands of trial cells to partners, and eventually scale to 200 MWh/year. The experience at Geelong demonstrates many Li-S processes (cathode ball milling, lithium foil cutting, cell assembly) can be assembled into a continuous pilot line.

Each of these companies uses largely conventional equipment (mixers, coaters, vacuum ovens, assembly machines) with only limited modification for Li-metal handling. They confirm that Li-S production can leverage much of the existing Li-ion infrastructure, but typically with expanded dry-room capacity and air-free anode handling. In summary, pilot and pre-commercial Li-S facilities have been established in multiple regions, and key performance targets (yields, capacities) have been demonstrated.

B. Electrode and Cell Fabrication Techniques

The cathode in a Li-S cell typically consists of Sulfur infused in a conductive matrix. As in Li-ion, the standard fabrication is

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a slurry process: mix active (carbon–Sulfur composite), conductive additive, and binder (e.g. PVDF or PTFE) in a solvent, coat onto Al foil, then dry and calender. This approach is already optimized in industry, with high throughput and tight quality control. Alternative methods such as dry pressing (no solvent) and freeze-drying (freeze a water-based slurry then sublimate) have been investigated, but these remain niche and have not yet displaced wet-coating for high-volume cell production.

On the anode side, Li-S cells use a lithium-metal foil or "lithium host" instead of graphite. Li-metal foil is produced by rolling and calendaring pure lithium or Li–alloy sheets. Very few manufacturers currently make Li foil at scale, so some Li-S makers (e.g. Lyten) are moving to produce their own battery-grade Li foil. Anodes may also use protective layers (solid electrolyte or polymer interlayer) to stabilize plating. Overall, Li-metal anode fabrication is more delicate than graphite – it requires strict humidity control and careful handling to avoid dendrites – but processes like foil cutting, stacking, and cell assembly can use similar tools to those for graphite anodes. For example, Li-S Energy's line has a "bespoke lithium foil anode cutting line" integrated into the roll-to-roll process.

Beyond electrodes, some hybrid cell architectures have been proposed (e.g. Li-S cells that pair Li-metal with a thin graphite layer, or use bipolar stacking), but these remain experimental. In mainstream Li-S manufacturing, the cell assembly (lamination of foil layers, electrolyte filling, formation cycling) follows Li-ion protocols. Notably, Lyten reports that its Li-S cells can be built in cylindrical or pouch formats on fully-automated lines – the same formats used in Li-ion production. The main difference is the electrolyte (Li-S typically uses ether-based electrolytes, which are flammable and require inert gas filling) and the need for even more rigorous dry-room conditions (for Li-metal). Li-S makers thus employ standard electrolyte mixing tanks and vacuum filling machines, often adding $LiNO_3$ during mixing to protect the Li surface. Overall, cathode and anode fabrication in Li-S is a modest extension of Li-ion methods, with key variations: higher carbon content in the cathode to conduct electrons through Sulfur, avoidance of toxic binders like NMP, and specialized handling of lithium metal (often in gloveboxes).

C. Scaling Challenges: Li-S v/s Li-ion

Lyten's milestone shows that existing Li-ion equipment can be repurposed for Li-S. Rolling coaters, calenders, laminators and formation cyclers need no fundamental redesign. The conversion of Li-ion lines to Li-S (adding Li-metal handling capability) took only ~6 weeks in one case. However, some equipment must be modified: e.g. dry-room capacity must increase to handle Li-metal safely. Binder mixing may switch to aqueous or alternative systems (since NMP can be omitted). In summary, capital equipment barriers are relatively low because Li-S can "drop into" Li-ion lines, but manufacturers must install stronger humidity and oxygen controls and lithium handling tools.

Li-S uses ether solvents (DOL/DME) rather than cyclic carbonates. These ethers are highly flammable and volatile, requiring explosion-proof facilities much like Li-ion's NMP facilities. However, a major environmental win is that Li-S cathode processing can eliminate NMP entirely, avoiding toxic solvent recovery systems. The electrolyte itself may contain $LiNO_3$ or flame retardants, but these are handled in closed vats. Overall, the environmental control burden is comparable to or slightly lower than Li-ion (no NMP, but additional dry-room for Li).

Scaling always involves achieving high yields. Li-ion production lines routinely exceed 95–98% cell yields. Li-S pioneers are closing the gap: Lyten's pilot line already "consistently surpasses 90% yield" and projects >98% yield at full scale. This indicates that quality issues (e.g. Sulfur loading uniformity, electrode delamination) can be managed with current process control. Achieving this in new Li-S lines is a learning curve, but no intrinsic factor (e.g. dendrites) forces yield to stay low.

CONCLUSION AND FUTURE PERSPECTIVE

As discussed throughout this review, the technology is fundamentally limited by inter-related challenges including polysulphide shuttle effect, intrinsically low conductivity of sulphur species, significant volume expansion, and instability of the lithium metal anode. Great advances have been realised in advanced cathode engineering (porous carbon frameworks, heteroatom doping, hybrid composites), electrolyte innovations (high-concentration electrolytes, localised electrolytes, solid-state electrolytes, functionalised electrolytes), and interfacial strategies such as artificial SEI layers and protective anode coatings. Even though these approaches offer improved electrochemical performances, they usually necessitate complex material designs and controlled test environments that are difficult to scale up and to apply in practice.

Importantly, the field still suffers from a disconnection between laboratory-scale advances and realistic cell-level requirements, particularly at high sulphur loading and lean electrolyte conditions. Therefore, future work will have to address integrated system-level optimisation, scalability of materials design and manufacturability. Ultimately, the

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commercial viability of Li-S batteries will depend on the development of robust, cost-effective and application-relevant systems rather than incremental improvements in individual components.

The development of scalable and cost-effective material synthesis should be the focus of future research as many of the existing strategies- such as complex nanostructured hosts and multi-functional additives- pose challenges for industrial implementation. A key focus is to go beyond material level optimisation to integrated cell design where the architecture of cathodes, electrolyte chemistry and anode protection are co-engineered to work synergistically under realistic operating conditions. A key priority is the move from material level optimisation to integrated cell design, where cathode architecture, electrolyte chemistry and anode protection are co-engineered to work synergistically under realistic operating conditions.

From an application perspective, future investigations should be directed towards the development of standardised testing protocols and realistic performance metrics, enabling a meaningful comparison across studies and rapid industrial translation. Bridging the gap between academic innovation and commercial feasibility will, in the end, require close collaboration among materials scientists, electrochemists and industry stakeholders. The practical realisation of Li-S batteries will rely on the development of robust, scalable and economically viable systems that can meet the demanding requirements of real-world applications.

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