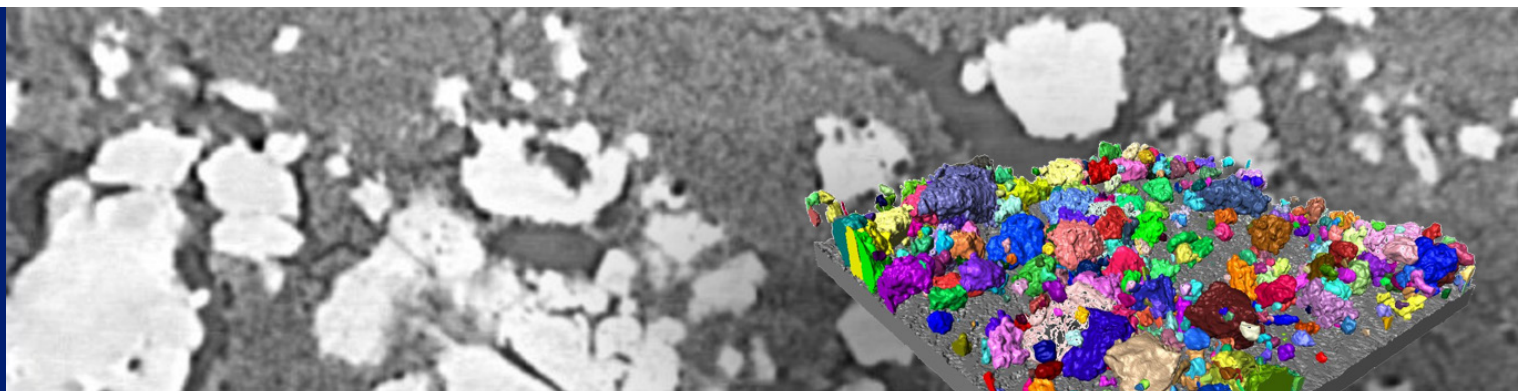


# Lithium-sulfur batteries: lightweight technology for multiple sectors



Lithium-sulfur technology has the potential to offer cheaper, lighter-weight batteries that also offer safety advantages. After initially finding use in niche markets such as satellites, drones and military vehicles, the technology has the potential to transform aviation in the long-term. Electric aircraft offering short-range flights or vertical take-off and landing (including personalised aviation and flying taxis in cities) are distinct possibilities by 2050. The UK, which is already home to established lithium-sulfur battery manufacturers and to leading academics in the field, has a great opportunity to be *the* global leader in this ground-breaking technology.

## Introduction

Batteries that extend performance beyond the fundamental limits of lithium-ion (Li-ion) technology are essential for the transition away from fossil fuels. Amongst the most mature of these 'beyond Li-ion' technologies are lithium-sulfur (Li-S) batteries. Li-S cells replace the metal rich cathode of Li-ion cells with comparatively cheap and abundant elemental sulfur, a material that also offers the theoretical potential for a five-fold improvement in capacity<sup>1</sup> for the same weight compared with materials widely used in Li-ion cells. By using sulfur, lightweight cells can be produced using more cost-effective materials, while also reducing the environmental and social concerns surrounding the production of nickel and cobalt. A comparison of some of these key metrics can be seen in Figure 1.

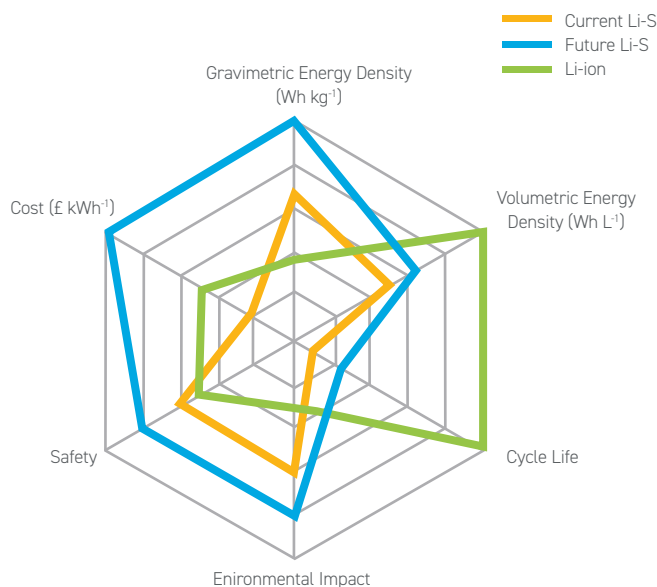
In contrast to some other battery types, such as Li-ion and Na-ion batteries, which employ an intercalation

**Batteries that extend performance beyond the fundamental limits of Li-ion technology are a prerequisite in the transition away from fossil fuels. Amongst the most mature of these 'beyond Li-ion' technologies are lithium-sulfur batteries, which have the potential to be a cheaper, lighter and safer technology than Li-ion.**



mechanism,<sup>2</sup> in which Li-ions are shuttled between electrodes where they are stored, Li-S batteries operate by a 'conversion mechanism'. In this process, elemental sulfur and lithium react to form a series of lithium-containing sulfur

**Figure 1: A comparison of the benefits toward key metrics offered by current and future Li-S and Li-ion battery technology**



<sup>1</sup> Capacity relates to the total energy stored by a battery. This has a key role in determining how long a battery will operate for during a single discharge.

<sup>2</sup> Intercalation refers to the process in which ions are stored between the layers of graphite in the anode. This process enables the battery to deliver the electricity stored in the cell.

compounds, known as polysulfides, to deliver the energy stored in the cell. This mechanism of operation improves the gravimetric energy density (the energy stored for a given weight<sup>3</sup>) of the device compared to the current generation of batteries by enabling the use of lithium metal, the lightest solid element, at the anode.

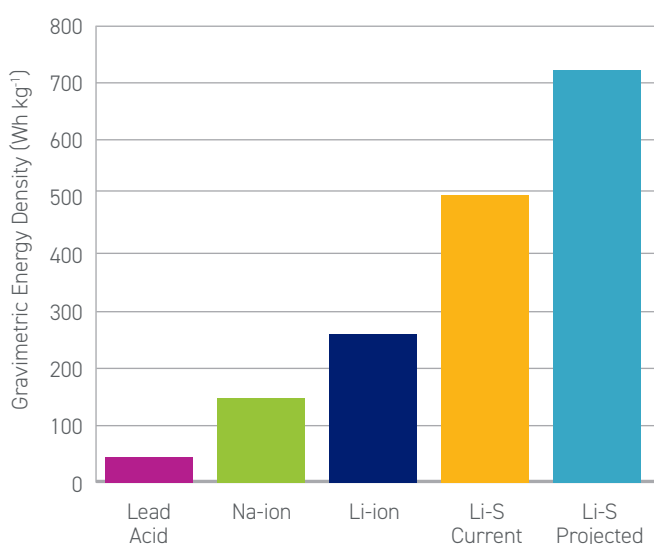
Historically, the majority of Li-S research has focussed on developing new materials to improve the sulfur cathode. However, in recent years there has been a recognition that developments are needed across the cell to improve the performance of Li-S batteries and offer a viable alternative to the widespread Li-ion cell.

Li-S batteries offer a number of advantages in comparison to current battery technology including (1) an improved gravimetric energy density, (2) a significantly reduced raw materials cost, (3) improved safety characteristics and (4) a reduced environmental burden associated with the cell materials.

## 1. Higher Energy Density

The most significant advantage that Li-S batteries offer over competitor battery technologies is their substantially higher energy density per unit weight.<sup>4,5,6</sup> Li-S cells have a theoretical energy density of 2,700 Wh kg<sup>-1</sup>. While this is reduced when deployed in a cell, the technology has been demonstrated at 470 Wh kg<sup>-1</sup> in a technologically relevant cell format.<sup>7</sup> Further improvements in the design of materials and

**Figure 2: Current and projected gravimetric energy density of Li-S batteries compared to state-of-the-art alternative battery technology. Adapted from data obtained from Lin et al.,<sup>4</sup> Hardwick et al.,<sup>5</sup> Faradion<sup>6</sup> and Oxis Energy<sup>7</sup>**



cells are expected to increase this to in excess of 500 Wh kg<sup>-1</sup> by early 2021. Figure 2 compares the energy density of Li-S batteries to alternative battery technologies. By moving beyond the limits of Li-ion batteries, Li-S cells will expand the range of applications in which electrification is currently possible, including into aviation and large vehicles.

## 2. Cost & Material Availability

Reducing the cost of batteries is amongst the biggest challenges facing manufacturers. Much of the cost of current batteries is due to the expense of metals including nickel and cobalt.<sup>8</sup> In contrast, the materials used in the electrodes of Li-S cells are comparatively low cost, with sulfur being amongst the most abundant element on earth. The benefits of economies of scale for Li-S cells will be realised upon wider commercialisation, in particular in the production of the electrolyte. Forecasts suggest this may lead to Li-S cells with comparable performance to Li-ion cells, but at less than half the price.<sup>9</sup> The removal of transition metals such as cobalt from batteries is also an important consideration due to environmental and ethical concerns with mining and uncertainties around security of supply.<sup>10</sup>

## 3. Improved Safety

Lithium-sulfur cells offer significant safety benefits over other battery types due to their operating mechanism. The 'conversion reaction', which forms new materials during charge and discharge, eliminates the need to host Li-ions in materials, and reduces the risk of catastrophic failure of batteries. Alongside this, the highly reactive Li anode is passivated with sulfide materials during operation, which further reduces the risk of a dangerous failure. While thermal runaway remains a possibility in Li-S cells, research has shown that the magnitude of this failure is significantly lower than Li-ion cells.<sup>11</sup> Li-S technology that employs a protective solid-state layer at the anode will also mitigate the risk of short-circuiting of cells. The conversion mechanism also enables Li-S cells to be stored safely for extended durations and shipped in a fully discharged state, which enables transportation via air freight as the cell is not unstable at low discharge states unlike Li-ion batteries. These inherent safety benefits will greatly aid the rapid uptake of Li-S cells and reduce the burden required for external safety components in a battery pack.

## 4. Improved Environmental Impact

As battery technology is deployed more widely the environmental impact of the cells, and their constituent materials, is becoming an increasing concern. As highlighted previously, Li-ion batteries typically contain both nickel and cobalt; materials which, at present, are obtained through intensive mining efforts. Alongside this, there are significant social concerns, in particular regarding cobalt supply chains, the vast majority of which is obtained from mines in

<sup>3</sup> Gravimetric energy density defines battery capacity in weight terms, i.e. Watt hours per kilogram (Wh/kg).

<sup>4</sup> Lin et al. *Nature Nanotechnology*, 12, 2017

<sup>5</sup> Bruce et al. *Nature Materials*, 11, 2012

<sup>6</sup> Faradion website

<sup>7</sup> Oxis Energy Press Release: January 2020

<sup>8</sup> Lithium, Cobalt and Nickel: The Gold Rush of the 21st Century, Faraday Insights, Issue 6, 2020

<sup>9</sup> Yang et al. *Energy*, 201, 2020

<sup>10</sup> Building a Responsible Cobalt Supply Chain, Faraday Insights, Issue 7, 2020

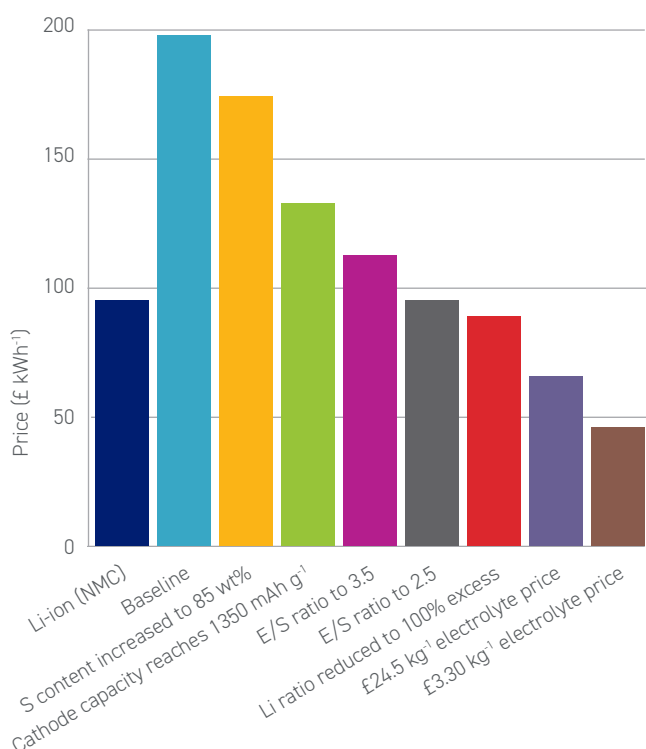
<sup>11</sup> Huang et al. *Energy Storage Materials*, 30, 2020

the Democratic Republic of Congo as detailed by a recent Faraday Insight.<sup>10</sup> These metals can have a significant contaminating effect on water supplies, and subsequently wildlife and food supplies.<sup>12</sup> In contrast, sulfur is so abundant that the US Geographical Survey has described it as ‘almost limitless’ and is geographically dispersed with significant production capacity across all continents.<sup>13</sup> In addition, environmental agencies do not consider sulfur to pose any major health risks.

### Li-S Batteries for Commercial Applications

Lithium-sulfur cells are most appropriate for applications that require high-energy rather than ‘power’ cell<sup>14</sup> applications. Despite this, the potential markets for Li-S are extremely broad. As with all early stage technologies, the initial deployment of cells over the next five years will likely be in niche markets including satellites, drones and in the defence sector for both personalised power and heavy vehicles. In these areas, the benefits of the lightweight nature of the cell exceeds the current comparatively high cost of manufacture (approximately £200 kWh<sup>-1</sup>).<sup>9</sup> However, as the technology matures and economies of scale reduce this price, Li-S will find wider use in the vehicles sector.

**Figure 3: Dependence of the price per kWh of Li-S cells on parameters showing the impact of developments on the cell price. Adapted from Yang et al<sup>9</sup>**



As illustrated by Figure 3, the cost reductions that will be seen for Li-S batteries will arise from both technological and economic advances. Developments in the cathode, including reducing the amount of conductive carbon and increasing the sulfur content alongside a reduction in the amount of electrolyte required in the cell (the electrolyte to sulfur ratio or E/S ratio) and the fabrication of thin anodes to reduce the excess Li in cells may yield a 55% reduction in the cost compared to the current baseline. In parallel, the commercialisation in Li-S cells will reduce the current high costs of approximately £48.50 kg<sup>-1</sup> associated with the manufacture of the electrolyte. Should this cost reduce to closer to that of Li-ion electrolytes (£3.30 kg<sup>-1</sup>) a further 22% cost reduction compared to the baseline case could be achieved.

The first deployment of Li-S cells in the context of transport is likely to be in heavy vehicles, which require enhanced gravimetric energy density, for example, trucks and buses, which have the space to accommodate relatively large cells. A recent announcement by Li-S developer Oxis Energy has outlined a plan to replace all diesel-powered buses in Brazil over the next 25 years.<sup>15</sup> Improvements in the power density of cells and a corresponding increase in volumetric energy density may enable deployment of Li-S technology in SUVs and light commercial vehicles either as the primary power source or in a hybridised unit. The expected low cost of the cells may also enable Li-S to be competitive with the lithium iron phosphate and Na-ion cells in two- and three-wheel vehicles, which comprise the majority of electrified transport in the developing world.

### Li-S as a Transformative Technology – ‘Electric Aviation in 2050?’

One of the most promising markets for Li-S cells is in the electrification of aviation, with substantive decarbonisation benefits arising from the transition from fossil-fuels to battery technology. The aviation industry accounted for 2.4% of global carbon emissions in 2018, with emissions set to treble by 2050.<sup>16</sup> Li-S cells are likely to be particularly used in the electrification of short-range aircraft, which is expected to have a sizeable operating market in domestic and short-range flights by the middle of the century. Indeed, UK government projections indicate the hybrid-electric aviation market could generate up to £4 trillion in the period to 2050.<sup>17</sup>

Prior to the COVID-19 outbreak, the UK saw approximately 520,000 domestic flights per year, with these typically being less than 500 km. Short duration flights are among the least environmentally friendly per passenger km<sup>18</sup> due to take off being the most power intensive phase of a flight. Indeed, a short or domestic flight emits approximately 180% of the quantity of CO<sub>2</sub> per passenger km of a medium or long-haul flight.<sup>19</sup>

<sup>12</sup> ABC ‘Whim Creek copper mine faces questions over possible Pilbara river pollution’, August 2019

<sup>13</sup> US Geographical Survey, Sulfur Statistics and Information, 2019

<sup>14</sup> ‘Power’ cells refer to cells that have the ability to deliver large currents per unit density i.e. Watts per kilogram (W kg<sup>-1</sup>)

<sup>15</sup> PV Magazine, ‘Brazilian buses to help drive down cost of lithium-sulfur batteries’

<sup>16</sup> The International Council on Clean Transport, CO<sub>2</sub> emissions from commercial aviation, 2018.

<sup>17</sup> Aviation 2050 – The Future of UK Aviation, Department of Transport, 2018

<sup>18</sup> A passenger kilometre refers to the transport of one passenger over one kilometre

<sup>19</sup> 2018 Government GHG Conversion Factors for Company Reporting: Methodology paper for emission factors: final report, Department of Business, Energy and Industrial Strategy, 2018

As well as playing a role in the decarbonisation of aviation, Li-S batteries may facilitate emerging technologies including vertical take-off and landing (VTOL), which offers the potential of personalised aviation and flying taxis in urban areas. The increasing commercial adoption of Li-S cells will be of great benefit to the UK's historically strong aviation sector, which ranges from global manufacturers to SMEs and has been estimated to provide £22bn annually to the UK's GDP.<sup>20</sup>

### Global Commercial Activity in Li-S Batteries

The UK-based Li-S developer, Oxis Energy has targeted a cell level energy of at least 500 Wh kg<sup>-1</sup> by the end of 2020.<sup>7</sup> Wider spread manufacture of their technology is expected with the imminent opening of a battery production plant in Minas Gerais in Brazil<sup>21</sup> and plans to open a plant to produce electrolyte and cathode materials in Port Talbot, Wales which will begin operation in late 2021.<sup>22</sup>

The challenges in manufacturing Li-S cells across all components has, in the past, led to companies using core technology in Li-metal anodes, developed with Li-S in mind, with Li-ion cathode materials to form a cell. Sion Power have released their Licerion® technology, which claims 500 Wh kg<sup>-1</sup> in a rechargeable cell.<sup>23</sup> A similar technology has been developed by PolyPlus that uses a thin glass layer to protect the Li anode; the company are also active in Li-S electrolyte development and project battery performance to be over 400 Wh kg<sup>-1</sup>.<sup>24</sup> Bodi Energy also maintain an interest in the development of Li-S electrolytes through their combined electrolyte/separator technology. Of the major Li-ion companies, LG Chem has the most substantial patent portfolio in the Li-S field; however, as yet, it has not released any Li-S products.

The significantly improved energy density of Li-S batteries compared to Li-ion has led to these cells being targeted at high-margin applications in which weight is a premium although there is a clear desire to expand the range of applications in which Li-S technology may be deployed.

### Building a British Industrial Hub

At this early stage of commercialisation of Li-S batteries, the UK has an opportunity to become a global hub for this technology. As a nation, the UK boasts established Li-S manufacturers, some of the most recognised academics in the field and the Faraday Institution's LiSTAR programme, which acts as the main focal point for research efforts.

Beyond this however, there is huge scope to link early commercialisation with established businesses including the aviation and automotive industries. The wider manufacturing requirements for Li-S cells are also well supported by an existing industrial eco-system, with the UK having a recognised expertise in the design of high-quality materials. Finally, the high-quality systems engineering capabilities that support current manufacturing are well placed to support the design and construction of Li-S battery packs and enable the

rapid implementation of developments. By taking advantage of the existing strengths and encouraging cross-sector work, combining academic and industrial expertise, the UK is in a strong position to be at the forefront of this emerging market over the next 20 years.

### Challenges in Lithium-Sulfur Batteries

Despite being researched since the 1970s, Li-S technology has not achieved the widespread commercialisation of other battery types due to a number of issues, which occur across the cell.<sup>25</sup>

The power offered by Li-S cells has historically been insufficient to enable the benefit of the lightweight nature of the cell to be fully realised. As the sulfur used in the cathode is not electrically conductive, carbon is typically added in relatively high quantities to improve the cells' performance. Improved strategies to reduce the amount of carbon required and design structured electrodes will improve the power density of Li-S cells. Further challenges to the power of cells arise due to the low solubility of polysulfides in the electrolyte and the rate at which the polysulfide products react during the discharge in current cell designs. To overcome these issues, materials that increase the rate of the reactions can be incorporated into the cathode to promote improved performance while extensive research is underway to improve the electrolytes used.

The cell suffers from a phenomenon known as the polysulfide shuttle effect, in which the polysulfides formed during cell operation shuttle back and forth between the electrodes, causing a loss of active sulfur from the cathode. This shuttle effect is part of a wider challenge with the Li metal anode, which can react with the electrolyte reducing the lifetime of the cell. Indeed, the challenges faced at the interface between the anode and electrolyte are perhaps the most crucial to solve in order to maximise the commercial prospects of Li-S cells. The use of a solid layer to protect the Li anode and the design of materials to 'trap' polysulfides and to reduce the shuttle effect are amongst the most promising ongoing research areas.

The sulfur used at the cathode also undergoes significant expansion as it reacts during discharge. This expansion can result in fracturing of the cathode and a loss of electrical connectivity in the electrode, in turn, reducing the number of charge and discharge cycles a cell can undertake. By designing expansion tolerant electrodes, the negative effects of this reaction can be reduced, improving the lifetime of the cell. This approach should also facilitate an increased amount of sulfur in the cathode and consequently a higher cell performance.

Developments in any one of these areas will result in improved cell performance; however, to maximise the benefits offered by Li-S cells improvements must be made across all the components of the battery.

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<sup>20</sup> Sustainable Aviation: UK Aviation Industry Socio-Economic Report

<sup>21</sup> Oxis Energy Press Release: May 2020

<sup>22</sup> BBC, 'Port Talbot battery plant to create hundreds of jobs'

<sup>23</sup> Sion Power website

<sup>24</sup> PolyPlus website

<sup>25</sup> Bhargav et al. Joule, 4, 2020



### The Faraday Institution's Li-S Research Project

The Faraday Institution's Lithium-Sulfur Technology Accelerator (LiSTAR) project,<sup>26</sup> led by University College London with six other university partners and seven leading industrial partners, is researching the development of Li-S batteries with a mission to improve the technology 'from the atom to the device.'

LiSTAR's four work packages are focussed on improving the critical areas to accelerate the commercialisation of these devices by:

1. Designing advanced cathode architectures, which maximise the sulfur content and accommodate swelling during operation and include catalytic components to improve the performance of cells.
2. Improving the fundamental understanding of the reaction mechanisms in cells, enabling the development of new, safer electrolytes and incorporation of new materials that can improve the efficiency of the battery and mitigate the polysulfide shuttling effect.
3. Developing advanced computational techniques to facilitate the materials design process and understand the key degradation pathways in Li-S cells.
4. Implementing novel anode designs and wider project developments into commercial cell formats through advanced engineering techniques.

To ensure the developments achieved in the project are of commercial interest the project is aiming to demonstrate improvements on a technologically relevant scale. Approaching the challenges of Li-S using a 'whole cell' approach will enable current barriers to widespread commercialisation to be overcome, catalysing industrial development in Li-S batteries.

### About the Faraday Institution and Faraday Insights

The Faraday Institution is the UK's independent research institute for electrochemical energy storage research and skills development. We bring together academics and industry partners in a way that is fundamentally changing how basic research is carried out at scale to address industry-defined goals.

Our 'Faraday Insights' provide an evidence-based assessment of the market, economics, technology and capabilities for energy storage technologies and the transition to a fully electric UK. The insights are concise briefings that aim to help bridge knowledge gaps across industry, academia and government. If you would like to discuss any issues raised by this "Faraday Insight" or suggest a subject for a future Insight, please contact Stephen Gifford.

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