THE ROYAL SOCIETY

Climate change and batteries: the search for future power storage solutions

In brief

More powerful, longer-lasting, faster-charging batteries are required for low-carbon transport and stable electricity supplies in a net zero world. Sustainable batteries will also need to use abundant materials and zero-carbon manufacturing processes. Rechargeable batteries are the most efficient way of storing renewable electricity, although weight, volume and cost make some applications impractical. They are needed to store the energy to power electric cars, drones, light aircraft, and increasingly for larger vehicles, as well as for storing electricity in the short term on highly decarbonised micro and larger electricity grids to ensure grid stability. They are currently thought unlikely to deliver very large energy storage for example to balance inter-seasonal grid variations. Lithium-ion batteries (LIBs) are currently the most viable short-term battery technology for these applications. LIB-related research is focusing on increasing energy density, reducing cost, extending longevity and battery recycling and reuse. For the longer-term, researchers are exploring a next generation of batteries using other materials and technologies to enable more widespread electrification of the economy.

INSIGHTS

- Research on lithium ion batteries will result in lower cost, extended life, enhance energy density, increase safety and speed of charging of batteries for electric vehicles (EVs) and grid applications.
- Research and regulation could lead to the building of batteries that are more sustainable, easier to recycle and last longer.
- Co-ordinated international effort should focus on identifying and testing new earth abundant materials to reduce costs, expand the use of batteries and minimise the environmental impact of battery production.
- Given enough focus, radically new types of batteries will be developed that have even lower costs and substantially higher energy densities.

1. Battery energy storage and climate change

Battery cell prices have come down in cost from over $1,000 per kilowatt-hour (kWh) in 2010 to below $150/kWh

1.1 Context

The primary source of global zero carbon energy will increasingly come from electricity generation from renewable sources. The ability to store that energy using batteries will be a key part of any zero-carbon energy system. Batteries will have an important role to play in decarbonising transport, as well as acting as the primary storage medium for decarbonised microgrids, self-sufficient power systems serving neighbourhood-scale communities, and as the means of stabilising large electricity grids. They will also be used more widely in industry to power motors, heaters, compressors and machinery.

Transport is responsible for 24% of direct CO_2 emissions from fuel combustion[1]. Motors powered by electricity stored in batteries are the leading contenders to replace fossil fuelled engines in many forms of automobiles and light duty vehicles. Even fuel cell powered vehicles will be equipped with a support battery. The important parameters for any battery type are energy density – how much energy it holds per unit of weight or volume and lifetime. Lifetime is measured in terms of cycle life, the number of times it can be charged and discharged, and calendar life, the time for which it can be stored measured in years.

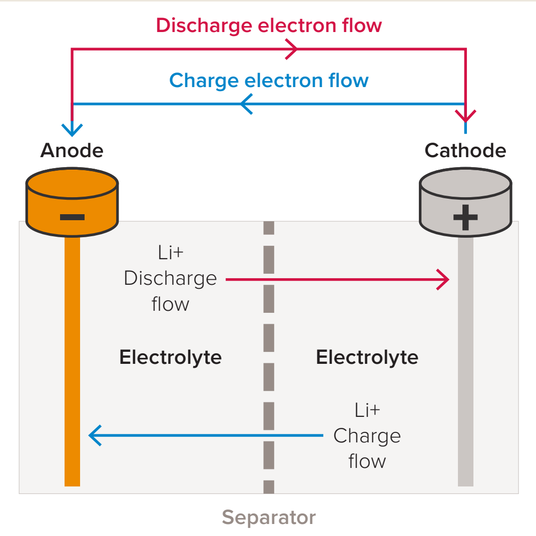
The market for rechargeable batteries for new applications is currently dominated by lithium-ion batteries (LIBs). They were originally developed for mobile phones and laptop computers and are now used at larger scales in electric vehicles (EVs), satellites and other devices. LIBs are powering growing volumes of electric cars, with the global EV fleet (including hybrids and full EVs) reaching more than seven million in 2019 and numbers are projected to grow to 150-250 million by 2030[2]. Battery cell prices (i.e. excluding packaging costs) have come down in cost from over $1,000 per kilowatt-hour (kWh) in 2010 to below $150/kWh[3], reaching $100kWh in some reports[4]. Costs of below $100/kWh are widely estimated to represent the point where batteries start to be competitive with ICEs, and recent reports suggest that this cost target has already been met in some sectors.

The typical range of a new EV is now around 200 miles[5], but the ability to charge rapidly and the cost of larger batteries remain challenges. Significant progress has been made in the laboratory: for example, researchers have reported a battery projected to last 10,000 charge-discharge cycles, equating to around two million miles of travel[6], but long calendar life also needs to be ensured, along with cheaper yet high energy density commercial cells in larger battery packs.

In electricity grids, batteries have become available at the scale and cost needed for short term (generally less than 90 minutes) extra power at peak demand times[7] to back up renewable generation. Total battery capacity in stationary applications has been projected to rise from around 11GWh to 420GWh in 2030[8]. Costs of utility-scale batteries in the US have fallen by around 70% since 2015[9]. However on a global level, the challenge of cost, as well as those of energy density and the massive scale required to compete with alternatives such as hydroelectricity and compressed air, have so far prevented batteries from being used for long-term storage (more than 24 hours). The use of batteries in electric vehicles has a role to play in grid storage in both micro and national electricity grids, as they can be used to feed electricity into the grid as well as taking electricity from it. This development presents the challenge of expanding the grid to provide more energy, but also the opportunity to access extra sources of grid storage and grid balancing.

BOX 1

How Lithium-ion battery cells work



The main components of a LIB are the two electrodes – the anode and cathode, the electrolyte – a liquid, gel or solid substance and a porous polymer separator which is soaked with the electrolyte. The electrolyte is usually formed of a lithium salt dissolved in an organic solvent. Various additives are added to electrolytes to enhance safety and performance.

When in use, or discharging, the (negative) anode releases electrons that flow through the external device such as a motor, before returning to the (positive) cathode side of the battery. To balance this electron flow, positively charged ions, or cations, flow within the battery from the anode through the electrolyte and separator to the cathode where they are reunited with the electrons. The flow is reversed when charging, with the ions returning to the anode.

The gain of electrons at the cathode is known as reduction and the loss of electrons at the anode is known as oxidisation, with the entire reaction being known as a 'redox' process.

It is worth noting that there is no metallic lithium in a LIB battery. The ability of lithium ions (Li+) to intercalate – or insert – into solid electrodes rapidly and reversibly, and with a wide range of voltages, enables the construction of a high-voltage cell. The cathodes are typically made from lithium transition metal oxides such as lithium nickel manganese cobalt oxide (NMC) and lithium iron phosphate (LFP). Anodes are generally made of graphite, used because of its competitive cost and its capacity to reversibly store many lithium ions without degrading. Aluminium and copper current collectors are typically used on the cathode and anode, respectively, to extract or insert the electrons. These are connected to the electronics external to the battery.

The amount of energy provided by a battery (its energy density – i.e. capacity x cell voltage) in one cycle determines, for example, an EV's range or the battery's contribution to grid balancing. Gravimetric energy density is expressed in watt-hours per kilogram (Wh/kg). The typical energy density of EV battery cells has increased from less than around 100Wh/kg in 1990 to over 250Wh/kg now[10 11].

The ultimate net zero ambition is for batteries to be made from recycled components, assembled in zero-carbon manufacturing processes.

1.2 High level challenges to battery implementation

There are several high-level challenges to the implementation of batteries to decarbonise energy use.

- **Cost:** Expense is an over-riding challenge and while the costs of EV batteries have decreased, an electric car with a reasonable range is still too expensive for many consumers. In terms of grid storage, while costs of utility-scale batteries have fallen, globally they remain too high to compete with options such as gas turbines or chemical storage of electricity using hydrogen or ammonia. However, they do have a vital role to play in short-term grid support such as voltage and frequency regulation. Furthermore, the fall in the cost of LIBs has been so great that there is currently often little financial incentive to make progress with newer battery technologies such as redox flow or sodium ion batteries. While they are currently more expensive, partly as they are not mass-produced, in time these have the potential to be cheaper and more sustainable.
- **Energy density:** While the energy density of LIBs has more than doubled since they were invented, it is still not enough to enable them to be used in heavy vehicles and airplanes[12]. In grid-scale batteries, gravimetric energy density is less critical, but barriers to battery use include cost, low volumetric energy density, compared with compressed hydrogen or ammonia, and the resource implications associated with the large sizes of the batteries needed for large scale storage of electricity on the grid. However, they will continue to be used for vital ancillary services and as the main storage for microgrids.
- **Longevity:** Research is focused on improving cycle life and calendar life. Both are determined by the gradual degradation of components, particularly the anode, cathode and electrolyte.
- **Scalability:** LIB batteries are comprised of small cells that are assembled to make larger battery packs. Inside the cells, the ions that are responsible for delivering energy are only around 0.2 nanometres in size, and they move in and out of particles that are microns in size (one seventieth of a hair's thickness). If they are to be of practical use, processes that work on these tiny dimensions need to be scaled, via increasingly efficient and automated manufacturing processes, to operate in progressively larger cells and battery packs – with scales and footprints measured in hectares.
- **Sustainability:** Sustainability challenges include finite raw materials, the working conditions of their miners, the carbon footprint of manufacture and limits on reuse and recyclability (see panel). The ultimate net zero ambition is for batteries to be made from recycled components, assembled in zero-carbon manufacturing processes.
- **Fast charging:** Higher charging speeds promote the uptake of EVs by enabling drivers to overcome 'range anxiety'. While many new EVs are now able to cover around 200 miles on one charge, the fastest current technologies are only able to charge a car to 80% in 20-40 minutes[13]. Better electrode designs and potentially new materials are required to allow safer, fast charging without reducing lifetimes. It also requires massive investment in the charging infrastructure.
- **Technology transfer:** Innovations have tended to take from seven to ten years (or more) from discovery to deployment, for example LIBs had an incubation period of around 20 years before commercialisation in 1991. Action is required now to meet 2050 goals.

2. Opportunities for progress and deployment

There are two main horizons for research into more powerful, longer-lasting batteries, each with its own focus:

- **Short term** – optimising LIB battery technology.
- **Long term** – developing next generation batteries with the potential to deploy batteries in a variety of critical applications.

2.1 Lithium-ion battery optimisation

2.1.1 Barriers to progress

There are few lithium compounds that can be used for electrodes that have a low enough cost, exhibit redox activity appropriate for a high voltage cell potential and have sufficient stability when lithium is extracted and reinserted over multiple cycles[14]. The most expensive component is the cathode, because of the costs of the redox active metals such as cobalt and nickel, and to a lesser extent the lithium, all of which need to be mined, processed and fabricated into a battery electrode[15]. Increased stability of battery components is critical: when batteries are assembled, the components are generally stable, and in their lowest energy state. However, when batteries are charged, many electrode materials become 'metastable', having a higher energy than they would in their most stable (or "equilibrium") state.

Today's LIBs can maintain these metastable states with minimum degradation and side reactions during normal operation. However, heat triggers structural changes towards the more thermodynamically stable materials leading to gradual battery failure. Fire risks occur if cathode materials change their structure too rapidly, giving off heat and generating oxygen, a process which is particularly severe in the case of a battery short circuit. Degradation at the cathode side is generally caused by structural changes that reduce capacity and increase resistance, in part by forming a cathode electrolyte interface or CEI, and in part by structural rearrangements of the surface and near-surface layers. On the anode side, batteries form a protection or passivation layer known as the solid electrolyte interphase (SEI) which has a double-edged effect. It is fundamental to performance as it prevents degradation of the electrolyte, protecting the electrolyte from the harsh reducing conditions of the anode. However, over time, growth of the SEI consumes and reduces the active lithium that can be inserted and removed into the anode and cathode materials and increases cell resistance.

There is scope to improve the energy density of LIBs to the 350Wh/kg that is currently considered to be their ultimate limit. However, net zero economies will in time demand batteries that exceed those limits. While potential new cathode materials are available, the challenge is to find materials which will not degrade rapidly or have potential safety hazards. The final barrier to progress is in rapid charging which can lead to overheating of the battery, which triggers multiple degradation processes. It can also lead to short-circuits which can in turn result in fires or explosions.

The long-term agenda involves going 'beyond lithium' to create batteries with greater energy density that are inherently more scalable and sustainable.

2.1.2 Potential for progress

Battery chemistry is an area where progress is being made in research, development and deployment. There are multiple opportunities for incremental advances in LIBs and a few examples are presented here:

- **Anode technology:** Use of silicon, or a silicon alloy or composite, instead of graphite, can theoretically increase energy density by about 40%[16]. However, batteries with silicon anodes suffer from more rapid capacity fade as lithium is trapped at the anode in electrolyte degradation products. Adding only limited amounts of silicon or silicon oxide (SiOx) to graphite may be used to provide modest capacity gains[17]. Lithium metal represents the ultimate in anode chemistry, and considerable research is being performed to devise strategies to prevent formation of lithium metal dendrites, needle-like structures that can cause power loss or short circuits, a serious safety challenge.
- **Cathode technology:** Nickel manganese cobalt oxide cathodes are operating close to their theoretical energy density limits. For some EVs, lithium iron phosphate is being used because the raw materials are highly abundant and relatively low in cost and reduce the overall size and weight of the battery pack[18]. Other structure types being explored and optimised include disordered rock salts[19], and compounds that potentially offer energy density gains of up to 50% (on the cathode) if stability issues could be solved. Optimising the morphology, or microstructure, of electrode particles presents another route to help improve performance, for example by helping to prevent particles from cracking.
- **Liquid electrolyte technology:** Electrolytes present further options for progress, with the chemistry of a range of solvents, salts and additives being examined to understand their transport properties and stability. Such improvements could increase the operating voltage and energy density of the cell, prolong its lifetime and improve safety. Opportunities exist for creating "designer" SEIs i.e. those created with bespoke coatings rather than relying on largely uncontrolled electrolyte degradation reactions.

2.2 Next generation batteries

While much research focuses on improving LIBs for the next decade, the long-term agenda involves going 'beyond lithium' to create batteries with greater energy density that are inherently more scalable and sustainable.

- **Sodium ion batteries (SIBs sometimes called NIBs):** Sodium has similar charge-carrying properties to lithium while being the sixth most abundant element on Earth, and relatively cheap as a resource. SIB cathodes can made from compounds where sodium combines with the relatively abundant, and cheap, iron and manganese oxides. SIBs generally have lower energy densities than LIBs, but if their costs can be brought down, this should not preclude them being deployed widely on the grid. They could also become suitable in EV applications where cost rather than range is critical, such as e-bikes[20]. China has already deployed the world's first energy storage facility using a 100 kWh NIB system at a research centre[21].
- **Multivalent-Cation Batteries:** The move to use cheaper metals with higher natural abundances has motivated a flurry of research activity on (in ascending order of difficulty) magnesium, calcium, zinc and aluminium batteries. These are known collectively as multivalent batteries. Batteries using such ions, could in principle, provide greater energy density. This field is in its infancy, and while the challenges are huge, the need for more sustainable batteries means that there are many strands of research to pursue.

- **Redox Flow batteries (RFBs):** Flow batteries use two chemical components (for example vanadium ions in different oxidation states), which are dissolved in liquids contained in separate tanks. To store electricity, the liquids are pumped through an electrochemical cell, containing positive and negative electrodes separated by a membrane to minimise "cross-over" of the solutions, into two new tanks. To discharge, the liquids are pumped back through the cell, reverting back into their original state (producing a current in the electrodes) and return to the original tanks. The promise of a RFB lies in the decoupling between storage (in tanks) and electricity generation (in the electrochemical cell), which means they can be readily scaled by simply using bigger tanks to increase capacity (MWh) or larger electrochemical cells to increase power output (MW). Vanadium RFBs have very long cycle lives and use safe, aqueous electrolytes. The first major (200MW/800MWh) battery using vanadium flow is under construction in Dalian, China[22]. However, vanadium RFBs have poorer energy densities than LIBs, as well as being toxic and having potential resource issues when used at large scales[23]. Batteries containing more sustainable and cheap organic chemicals such as quinones have considerable promise, but issues of long-term stability of the components remain an active area of research.
- **Solid state batteries:** Batteries that use solid electrolytes are also being examined as an exciting route forward. They have potential for increased safety and higher energy densities, particularly if lithium metal is used instead of graphite at the anode. All solid-state batteries are fabricated largely from ceramic components. These must be able to conduct lithium ions while maintaining good contact between electrode and electrolyte as the anode grows and shrinks on charging and discharging This is a significant challenge if high pressure is not applied to the cell. Soft sulphide-based electrolytes show extremely high lithium-ion conductivities – key for high-rate batteries – but are more reactive (both the cathode and anode materials with moisture and air). Polymers have been used as electrolytes, since they are easy to process and help improve safety, but their ionic conductivities are lower than liquid electrolytes motivating more research.

- **Longer term options:** Sustainability considerations have motivated considerable work on lithium sulphur and metal-air batteries, which have extremely high energy densities and potentially low cost. Lithium-air batteries (LABs) – where the reaction is between lithium and oxygen – represent the ultimate in energy density. However, the technology faces significant challenges, including severe electrolyte degradation issues, and the need for air handling to control carbon dioxide and moisture levels, which adds complexity and thus cost. However, recent advances have led to projections of 600Wh/kg for Li-air batteries, including the air handling. Such numbers may be crucial for electrification of aviation. Rechargeable zinc-air batteries are starting to show considerable promise, with progress, for example, being made in ability to plate zinc metal reversibly. Metal-sulphur batteries, with theoretical energy densities between those of LABs and LIBs are also closer to being commercial – but as in a LAB, the lithium metal anode needs to be protected and side (shuttling) reactions need to be prevented. Ultimately, scientists may need to develop yet unknown 'batteries of the future', which may look like a combination of a battery and fuel cell, where a range of cheaper and more sustainable chemicals are used reversibly as "energy vectors" or fuels, generating electricity via a series of oxidation and reduction reactions.

BOX 2

Sustainability

Circular economy principles for reuse and recycling are starting to be applied to LIBs. Today's batteries raise a series of sustainability issues, from the mining of finite materials to recyclability. In terms of materials, there are questions over future availability of nickel and cobalt as well as concerns over health, working conditions and human rights among cobalt miners[24] and the pollution risks of nickel extraction. Lithium is plentiful today, but if the battery market grows as projected and batteries are not recycled, known supplies may not meet demand or even run out within decades[25]. There are also environmental concerns at the point of extraction. The life-cycle carbon footprint of a battery derives almost entirely from its manufacture, with around half coming from the electricity involved in production[26]. While studies focused on batteries alone are rare, research in this area demonstrates that today's batteries do not yet represent a zero-carbon option. One study suggested that in a typical European context, emissions from manufacturing a vehicle's LIB generated a lifetime footprint of 27 grams per kilometre (g/km) of CO2, (rising to 50 g/km[27] if the battery was made in Asia) forming part of a total EV footprint of 109 g/km, compared to an average gasoline-fuelled car's 258 g/km. It is important to stress that as new technology comes on board, they must be accompanied by a full life cycle analysis, taking account of any potential new critical resource issues. In terms of other manufacturing factors, many electrodes are fabricated from flammable and toxic slurries[28], although aqueous processes with more environmentally friendly binders are increasingly being used for the anode.

Recycling is challenging as batteries are generally unsafe to open as toxic gases may be released and fire hazards are present and the different components are difficult to separate. Research is underway by the UK Faraday Institution and many others worldwide into ways to safely strip down batteries, including use of robotics, and recovery of reusable materials[29]. However, it is essential that recycling is designed into future batteries.

3. Key areas for future battery development

There are a number of key areas that require further development to optimise existing LIB battery systems and develop the solutions needed for the batteries of the future.

- **Characterisation:** Further tools need to be developed to probe battery health in batteries operating in real-life conditions. Better tools are also needed to characterise the material interactions within batteries.
- **Computation and modelling:** Understanding battery performance and degradation requires modelling to bridge computation at the atomic, battery component and battery pack levels. AI or deep learning methods have the potential to speed up research, allow larger systems to be modelled and handle the large data sets that emerge, but inherently also require careful modelling of the different processes themselves.
- **Control of metastable materials:** Metastability is fundamental to the operation of a battery and one challenge is to find materials which, for example, can withstand higher temperatures or are inherently self-healing.
- **Multi-disciplinary collaboration:** A multi-disciplinary approach, with sustained and long-term funding, is essential in battery research. Collaboration between academia and industry is evident in such initiatives as Batteries Europe[30], the Tianmu Lake Institute of Advanced Energy Storage Technologies in China[31], Batterie 2020 in Germany[32], the US Joint Center for Energy Storage Research[33] and the UK's Faraday Institution[34], for example, but there is scope to increase such international partnership working for global benefit.

3.1 What could be achieved by 2030 and by 2050 in terms of deployment?

By 2030, LIB technologies should benefit from a range of incremental, improvements that lower cost, extend life, enhance energy density and increase charging speed, while progress is made towards the long-term goal of going beyond today's technologies. While each improvement may only be modest, for example, replacing the entire graphite anode by silicon (still extremely challenging), together they could lead to an increase in capacity of up to 40%. Performance increases across multiple areas will result in more substantial advances and help increase adoption.

By 2050, breakthroughs should have been made to scale up larger batteries for grid storage, potentially by using sodium ion or new technologies that go beyond traditional rechargeable formats, such as redox flow batteries (RFBs) or an as yet unknown 'battery of the future'. The demands for electrification of HGVs and aviation will drive beyond LIB battery technologies. Meanwhile a net zero world of 2050 should also feature batteries that are made from sustainable materials and are fully recyclable, possibly using iron and manganese instead of cobalt and nickel if new chemistries are found and optimised and issues of degradation are solved.

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Conclusion

Batteries will continue to be key to the decarbonisation of electricity grids, transportation and powering much in the digital world. The further development of lithium ion batteries will be important in the short-term, fulfilling many of the roles that need batteries. However, the inherent challenges of the need for higher energy densities, issues with raw material cost and availability, as well as safety considerations, will continue to drive the development of new battery chemistries to complement existing LIBs and allow growth in different market segments. These will only come to fruition in the timescales required through focused international co-operation and co-ordination. Such collaboration and development offer the possibility to accelerate the rate of decarbonisation by increased electrification.

This briefing is one of a series looking at how science and technology can support the global effort to achieve net zero emissions and adapt to climate change. The series aims to inform policymakers around the world on 12 issues where science can inform understanding and action as each country creates its own road map to net zero by 2050.

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