European Commission

Science for Environment Policy

FUTURE BRIEF:
Towards the battery of the future

September 2018
Issue 20

Environment

Science for Environment Policy

Towards the battery of the future

Printed by the Publications Office in Luxembourg.
Luxembourg: Publications Office of the European Union, 2018

Print ISBN 978-92-79-84039-5 ISSN 2363-2771
doi:10.2779/503230 KH-BB-18-006-EN-C

PDF ISBN 978-92-79-84040-1 ISSN 2363-278X
doi:10.2779/674936 KH-BB-18-006-EN-N

This Future Brief is written and edited by the Science Communication Unit, University of the West of England (UWE), Bristol
Email: sfep.editorial@uwe.ac.uk

To cite this publication:
Science for Environment Policy (2018) *Towards the battery of the future.* Future Brief 20. Brief produced for the European Commission DG Environment by the Science Communication Unit, UWE, Bristol. Available at:
http://ec.europa.eu/science-environment-policy

Acknowledgements
We wish to thank the scientific advisor, Dr Jens Peters, Helmholtz Institute Ulm (HIU) for Electrochemical Energy Storage; Karlsruhe Institute of Technology (KIT), for his input to this report. Final responsibility for the content and accuracy of the report, however, lies solely with the author.

Images:
Reproduced with permission by the relevant author or publisher, or otherwise publicly authorised for use, as follows:
Pages 4&8: Fig. 1 Key components of a battery. Designed by Science Communication Unit, UWE, Bristol
Page 7: Batteries for renewable energy storage © getty images/Petmal
Page 10: Electric vehicle charging © getty images/https://www.facebook.com/PlargueDoctor/
Page 13: Lithium-ion batteries © getty images/SVproduction
Page 14: Congolese raw material © getty images/Nada3
Page 15: Mine tailings © getty images/francisblack
Page 18: Fig. 2 Battery production chain © MEET Battery Research Center, University of Münster
Page 22: Waste batteries at a metal recycling scrap yard © getty images/tfoxfoto
Page 26: Waste cylindrical batteries © getty images/kemalbas
Page 27: NASICON battery crystal structure © CC by 4.0. Materialscientist
Page 28: Redox flow batteries © Application Center Redox-Flow at the Fraunhofer Institute for Chemical Technology ICT
Page 31: Fig. 3 Printed battery diagram. Adapted from Nguyen, Fraiwan and Choi, 2014 by Science Communication Unit, UWE, Bristol
Page 32: Flexen printed battery © University of Cambridge
Page 34: Battery applications © getty images/TarikVision.

About Science for Environment Policy

Science for Environment Policy is a free news and information service published by the European Commission's Directorate-General Environment, which provides the latest environmental policy relevant research findings.

Future Briefs are a feature of the service which provide expert forecasts of environmental policy issues on the horizon. In addition to Future Briefs, Science for Environment Policy also publishes a regular **News Alert** which is delivered by email to subscribers and provides accessible summaries of key scientific studies.

http://ec.europa.eu/science-environment-policy

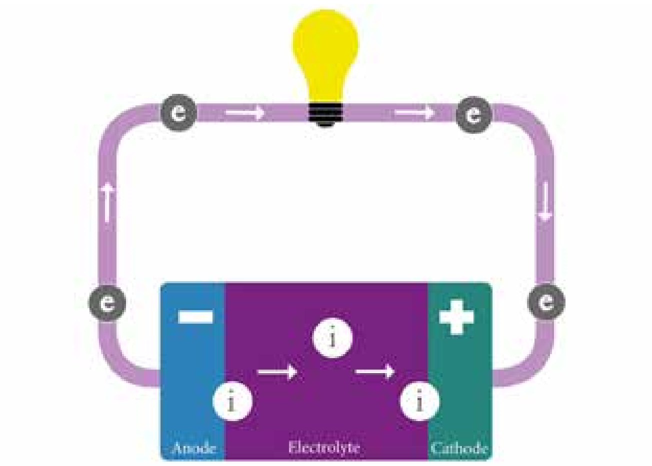
Keep up-to-date

Subscribe to Science for Environment Policy's **News Alert** by emailing:
sfep@uwe.ac.uk

Or sign up online at:
http://ec.europa.eu/science-environment-policy

Contents

Executive summary



This Future Brief from Science for Environment Policy provides an overview of technical aspects of battery design and production which enable the environmental footprint of batteries to be lowered. It highlights how battery technologies are evolving to deliver better performing batteries. High-quality and technologically innovative batteries are imperative for the EU in the context of its move towards a low-carbon, climate-friendly and more circular economy.

Batteries bring a number of environmental advantages. By enabling a greater share of renewable energy in the power sector, they help avoid negative environmental impacts of fossil fuel-or nuclear-based power, such as air pollution and its corresponding effects on human and ecological health, as well as greenhouse gas (GHG) emissions. Furthermore, materials in batteries can be recovered and recycled, some of them indefinitely – unlike fossil fuels, which are burned and lost forever when used for energy production.

However, manufacturing and using batteries, as well as the way they are treated at the end of their life, also has environmental impacts. This report explores aspects of battery design and manufacturing which may be considered in support of ambitions to develop batteries that are high-performing and have minimal environmental impact.

Many of these considerations relate to the materials used to produce batteries. There appear to be sufficient reserves of most of the key constituents of lithium-ion batteries – the most quickly growing form of technology on the battery market – to meet near-term and predicted increases in demand for batteries stemming from the rapid rise of electric mobility. However, we cannot rely on these reserves in the longer term, or in the event of a dramatic, unexpected increase in resource demand. The vulnerable supply chains for many of these materials should also be acknowledged.

In addition, concerns remain surrounding the toxicity and safety (e.g. flammability) of certain battery components. For instance, there are issues relating to some of the materials used in lithium-ion technologies, including active materials in the electrodes and electrolytes, notably cobalt, as well as the substances that bind electrode materials together.

There are many means of addressing these material issues in future battery designs. For instance, increasing the energy density of batteries (i.e. the amount of energy stored per litre or kilogram of battery) not only offers important benefits for battery performance, but also reduces pressure on resources and the impacts caused by battery production, as less material overall is needed to produce the same capacity of battery.

Various alternatives to toxic materials and/or materials with limited or risky supply are also being explored by scientists. Some discussed in this

report include sulphur, oxygen and sodium as active cathode materials. Technologies based on these materials could potentially lower the environmental impact as well as increase the performance, but they must overcome some major research hurdles before they can be considered market-ready. There are also challenges, as well as promising developments, in finding suitable substitutions for cobalt, used in lithium-ion cathodes, and fluorinated binders.

The energy needed to manufacture and charge batteries is another important consideration. The energy-intensive production of lithium-ion batteries is associated with high environmental impacts derived from electricity production, such as emissions of GHGs and air pollutants. Considerable environmental benefits can, therefore, be reaped by powering battery production facilities with renewable energy, and in locating battery plants in countries with relatively clean energy mixes.

The environmental impacts incurred by the energy used to charge batteries can be reduced by increasing roundtrip efficiency, that is, the ratio of energy that discharges from a battery, compared with how much is put in during charge. An important goal is to minimise the amount of energy that is lost during these charging cycles.

Extending the lifespan of batteries is also key to reducing costs, pressures on resources and negative impacts of both manufacturing and recycling by reducing the number of times that a battery needs to be replaced. Lifespan can be extended through technological enhancements, as well as by re-using older batteries, for example, repurposing ex-vehicle batteries for stationary energy storage applications.

Re-use and recycling are part of a circular economy approach. These lower the impacts of resource consumption and manufacture, provide a secure supply of secondary materials (in the case of recycling), and avoid the potentially toxic impacts of landfilling and incineration. Design features which make batteries easy to disassemble are important in supporting recycling and re-use.

Batteries are expected to simultaneously fulfil a large number of criteria in order to meet challenging combinations of consumer demands, such as high power and high-energy density, long life, low cost and excellent safety, and with minimal negative environmental impact. As this report demonstrates, there are certainly many opportunities to make improvements on existing technologies.

Many promising developments are taking place in the ongoing evolution of batteries. This report presents three case studies of emerging forms of battery: solid-state lithium-ion, redox flow batteries and printed batteries. These illustrate the potential of new battery technologies in meeting societal needs, such as effective energy storage, and in creating new opportunities for new types of products. The case studies also demonstrate some of the pros and cons of different combinations of design parameters.

It is increasingly evident that, for batteries, one size does not fit all. It is, therefore, important to identify the most appropriate type of battery for a particular application, in terms of both performance and environmental quality. This report does not, and cannot, predict which battery technologies will come to dominate in future, or which offer the best environmental profile. Instead, it serves to highlight areas of battery design where improvements can help ensure that future battery technologies are as environmentally sustainable as possible and continue to fulfil their valuable purpose.

Introduction

It is difficult to overstate the importance of batteries to our future as we currently envisage it. Batteries are critical in efforts to cut greenhouse gas (GHG) emissions and mitigate dangerous levels of climate change through their role in bringing secure supplies of clean, low-carbon energy to our homes, businesses and vehicles. Batteries are also hugely important in helping power the expanding digital economy and an ever-growing number of portable electronics.

The use of batteries allows greater penetration of (intermittent) renewables in the power sector and, thus, helps avoid the negative environmental impacts of fossil fuel- or nuclear-based power. This has particular environmental advantages for air quality and human health, as well as the climate. In relation to resource efficiency, materials in batteries can be recovered and recycled, some of them indefinitely, whereas fossil fuels – which are valuable for purposes other than energy production – are burned and lost forever.

Battery numbers are set to grow dramatically, particularly with the increase in electric mobility (e-mobility). However, manufacturing and using batteries, as well as the way they are treated at the end of their life, also has environmental impacts.

To alleviate these pressures, work is needed to better integrate batteries into a circular economy and cut their consumption of resources, including their use of some toxic and critical raw materials. Furthermore, emissions of GHGs and pollutants associated with their production and use should be reduced.

This Future Brief from Science for Environment Policy provides an overview of technical aspects of battery design and production which enable the environmental footprint of batteries to be lowered. It also shines a light on the future of batteries, by presenting a selection of promising technologies in case studies, discussing their potential performance, uses and characteristics which contribute to their environmental profile.

The European policy context for batteries

Batteries are a cross-cutting issue, relevant to many areas of policy, including transport, climate action, energy, waste and resources. Their development, production and use are imperative for Europe in the context of its move towards a secure, affordable and climate-friendly energy supply, as part of the **Energy Union**[1] strategy, and the competitiveness of its automotive sector.

The European Commission has recently proposed that the EU takes up the challenge of becoming a global leader in sustainable cell and battery manufacturing, able to compete with current manufacturing bases (mainly in Asia). In support of this ambitious goal, the European Commission launched the European **Battery Alliance**[2] cooperation platform in October 2017 and endorsed a **Strategic Action Plan on Batteries**[3] in May 2018 as part of the **Europe on the Move**[4] package of sustainable mobility initiatives. The Action Plan aims to put Europe on a firm path towards leadership in this key industry, supporting jobs and growth in a circular economy, whilst ensuring clean mobility and an improved environment and quality of life for EU citizens.

The Commission promotes a cross-border and integrated European approach to battery manufacturing, which focuses on sustainability throughout the value chain, starting with the extraction and processing of raw materials for batteries, through to the design and manufacturing phase, and their use, recycling and disposal in a circular economy context.

1. https://ec.europa.eu/commission/priorities/energy-union-and-climate_en
2. https://ec.europa.eu/growth/industry/policy/european-battery-alliance_en
3. https://ec.europa.eu/transport/sites/transport/files/3rd-mobility-pack/com20180293-annex2_en.pdf
4. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2018%3A293%3AFIN

The Batteries Directive[5], the only piece of EU legislation exclusively dedicated to batteries, aims to minimise the environmental impact of batteries. The Directive assumes that pollution caused by the substances contained in batteries is the main source of negative impacts on the environment These impacts can arise if batteries are landfilled, incinerated or improperly disposed of at the end of their life.

Faced with these risks, the Directive adopts a twofold approach: reducing the use of hazardous substances in the composition of batteries on the one hand and, on the other hand, ensuring that batteries are properly managed at the end of their life (for instance, the incineration of automotive and industrial batteries is prohibited). The Directive is currently undergoing review[6] and, as a result, will contribute to an innovative and future-proof regulatory framework for batteries.

With regards to the colllection of automotive batteries, the **End-of-life Vehicles Directive**[7] has been instrumental. It has contributed to meeting the high levels of recycling established by the Batteries Directive.

The European Strategic Energy Technology Plan (SET-Plan)[8], defines research and development priorities on energy and includes a specific Action on Batteries. This Plan is dedicated to promoting the competitiveness of EU industry in the global battery sector as a contribution to the development and deployment of low-carbon technologies. This is achieved through coordination of national research efforts and helping to finance projects. In addition, a New European Technology and Innovation Platform on Batteries will be soon established to facilitate closer co-ordination of national, private and EU efforts (as described in Europe on the Move documents).

Numerous research and innovation projects have also been supported by the successive EU's **Framework Programmes for Research and Innovation**. A recently published report[9] (Projects for Policy series) draws the main policy conclusions on the basis of 135 projects supported, which received a total of €555 million in EU and private funds.

5. http://ec.europa.eu/environment/waste/batteries/index.htm
6. http://ec.europa.eu/environment/waste/batteries/evaluation.htm
7. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02000L0053-20130611&qid=1405610569066&from=EN
8. https://ec.europa.eu/energy/en/topics/technology-and-innovation/strategic-energy-technology-plan
9. https://trimis.ec.europa.eu/content/batteries-major-opportunity-sustainable-society

Section 1. An introduction to batteries

This section introduces key technical concepts to aid comprehension of the report. It also outlines some of the main issues that influence the development of new battery technologies.

Batteries come in many shapes and sizes – from the size of a postage stamp to the scale of a warehouse – and use numerous chemical compositions. This diversity creates a range of opportunities for energy management and for powering electronics and vehicles. It also presents varied challenges in determining their environmental impact or appropriate end-of-life handling (i.e. recycling).

1.1 How a battery works: the basics

A battery converts chemical energy into electrical energy. It is typically made of three major active components: an **anode**, a **cathode** and an **electrolyte**. These are each made of a different material and, in very basic terms, chemical reactions between the materials generate energy.

The chemical reactions mainly occur when the battery is plugged into an external circuit that connects the anode and cathode, for example, when it is placed into a mobile phone or a car.

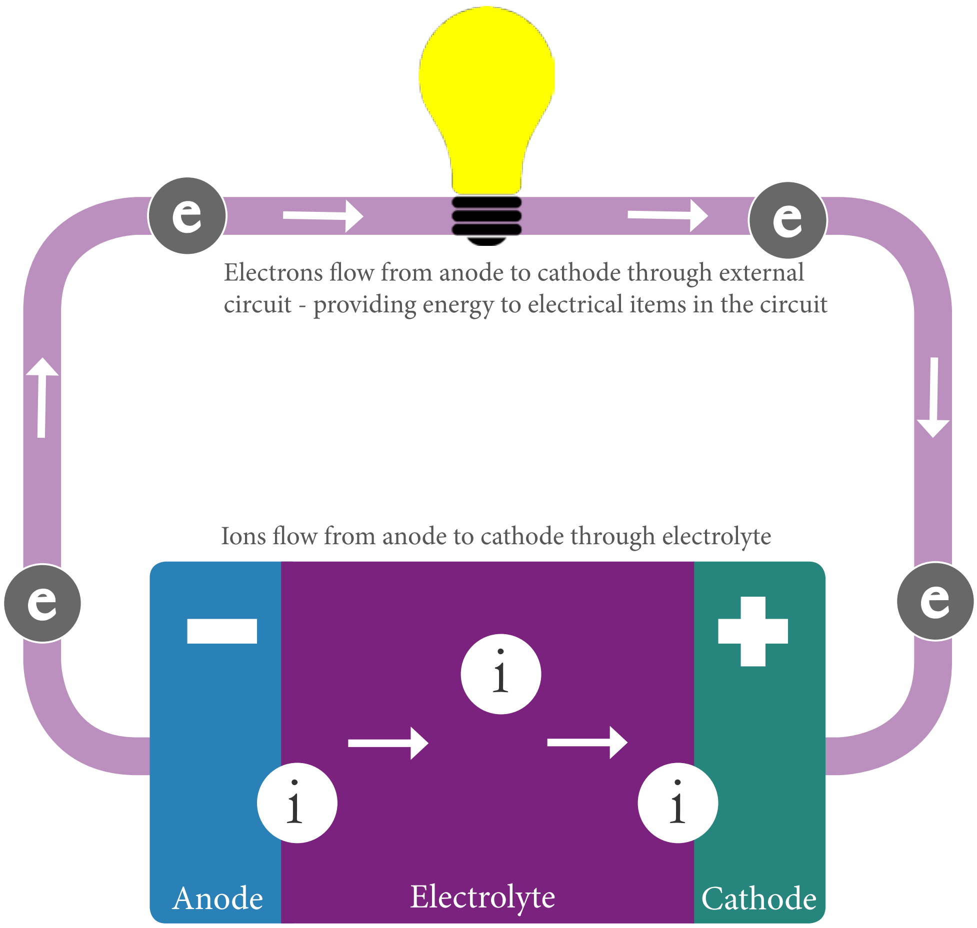


Figure 1. Diagram illustrating key components of a battery, and the flow of ions and electrons in an electrical circuit

The reactions cause **electrons** and **ions** to build up at the anode. The electrons flow towards the cathode through the external circuit where they provide electrical power en route (to the phone or car, for instance).

The ions also flow towards the cathode, but through the electrolyte which separates the anode (also known as the **negative electrode**) and the cathode (also known as the **positive electrode**). The ions and electrons recombine at the cathode to complete the circuit and keep the reactions running.

1.2 Battery architecture

The anode, cathode and electrolyte make up one **cell**, along with other key components, such as the **binder**, which holds particles of the active material together. A battery can be made up of one or more cells which are connected to increase the voltage and/or the total storage capacity of the assembly.

The cells can be assembled into a **module**, and the modules then placed in a **pack**, to be inserted into the application (e.g. a car). Other key auxiliary components, such as cooling equipment or a battery management system (an electronic system within the battery pack for controlling and monitoring the battery), may be needed as part of the overall battery **system**.

There are, thus, a number of important components of batteries and battery systems that do not directly take part in chemical reactions, but which are still needed to allow its proper functioning.

1.3 Rechargeability

The materials used for the electrodes and electrolyte determine the lifespan and rechargeability of a battery. In broad terms, batteries become discharged because the reactions slowly transform the materials into other chemicals, until they can no longer react. However, it is possible to reverse this chemical transformation by providing electric energy which switches the direction of both the electrons' and ions' flow. Rechargeable batteries, which are able to host the chemical reactions involved in two directions, are also known as **secondary batteries**. Non-rechargeable, single-use batteries, are known as **primary batteries**.

Historically, primary batteries have been used to provide short-term, grid-independent energy to portable applications, such as portable electronics. Until recently, secondary batteries (based on lead-acid technologies) have been predominantly used in automotive applications. Recent years have also seen the arrival of lighter, energy-dense secondary batteries, mostly based on lithium technologies, which have contributed to the spread of connected communication devices, such as smartphones and laptops.

1.4 Energy, power and energy management

Different forms of battery will have different energy-to-power (E/P) ratios. **Power** refers to the amount of electricity that can be instantaneously released by a battery, whereas **energy** is the amount of electricity stored over time. The ratio is determined by layout, materials and other factors, and affects a battery's suitability for different applications.

For instance, high energy is a primary concern for portable electronics, to extend usage time between charges, whereas stationary batteries in the electricity grid, notably batteries used to balance the difference between electricity supply and demand (frequency regulation), primarily need high power output for short times. Electric vehicles require both high power

(for acceleration) and high energy (to enable a long driving range).

Secondary batteries are also used in the energy sector to store energy from external sources, including intermittent renewable supplies (e.g. wind or solar), and release it when needed. In this usage, these batteries play a critical role in efforts to mitigate climate change and are often referred to as **energy storage** devices, although, technically speaking, all batteries store energy. High energy storage is a critical consideration for these batteries. Power output capabilities are a smaller consideration for such applications.

1.5 The future evolution of battery design

To meet the future needs of our society, a huge improvement in the performance of batteries is key, with new designs that meet specific purposes. Although batteries were, initially, a simple technology, their development has been very slow compared with other areas of electronics. A major research hurdle lies in finding suitable materials for electrodes and electrolytes – that actually work well together without undue compromise to other aspects of a battery's design. There is much trial and error in selecting the best combination of design parameters.

The competitiveness of batteries also depends on whether they meet challenging sets of consumer demands, whether those are to enable a competitively-priced electric car with a large driving range, or to provide more affordable, maintenance-free technologies for grid storage (Grey and Tarascon, 2017). In many cases, and certainly for e-mobility batteries, this means simultaneously fulfilling a number of criteria, such as high power and high-energy density, long autonomy, long life, low cost and excellent safety, while also minimising their negative environmental impact, for example, by ensuring that they are easy to re-use and recycle and based upon abundant resources. At present, no battery ticks all these boxes.

However, progress is taking place in battery design, and there are many promising developments in the ongoing evolution of batteries which enable improved performance and a better environmental profile. As this report highlights, many opportunities to reduce the environmental footprint of batteries are, very often, accompanied by better performance. Thus, there are both trade-offs and synergies to be found among many design considerations.

Ultimately, it may not be possible to develop the 'ideal' battery, which meets all the desired criteria, and the choice of battery for any given use will involve some compromise. It is increasingly evident that, for batteries, one size does not fit all, and so what is important is to identify the most appropriate type of battery for a particular application, in terms of both performance and environmental quality.

From the perspective of improving environmental performance, circular economy considerations are particularly important, as re-use and recycling can alleviate many environmental pressures across the lifecycle of batteries – including GHG and toxic emissions during production and use, and resource consumption (see **Section 2.4**). To fully embrace these considerations, a new approach to battery development is needed in which features that support recycling and re-use are built in to the battery's basic design (see **Section 2.4.3**).

Clearly, technology is only part of the solution to lowering batteries' environmental impacts. Socio-economic changes also need to be considered, such as recycling behaviour, consumer behaviour, waste management infrastructure and the economic factors that determine whether a recyclable material is actually recycled or not. Both policy action and technological research are, therefore, key. In addition, opportunities to avoid batteries by using alternative systems to store energy can also be explored.

A combination of battery technologies is likely to be in use in the future, although it is not yet possible to say which these will be, or to identify which type(s) will be the most environmentally sustainable. However, it is possible to highlight which areas of battery design need attention in order to ensure that future battery technologies are as sustainable as possible, whilst continuing to fulfil their valuable purpose. This report draws attention to those areas.

Section 2. Environmental issues for batteries

While batteries can potentially make our economy greener by reducing our reliance on fossil fuels, we also need to consider the environmental footprint of batteries themselves. This section highlights existing environmental issues with current battery technologies, particularly lithium-ion (see **Box 1**), and discusses how they could be addressed in the design of future batteries, including those currently in development.

This is not an exhaustive list of issues, and does not identify the 'greenest' battery, but presents a number of priority areas. It also shows some of the challenges and opportunities associated with balancing performance and sustainability characteristics.

Lifecycle analysis (LCA)

This section draws heavily on lifecycle analysis (LCA) research, which aims to calculate a product's environmental footprint across a range of impacts, including energy consumption, GHG emissions and effects of pollution, and over the product's lifecycle – from raw material acquisition or generation from natural resources to final disposal.

LCA can also be used to develop environmental labelling systems for products. Technical guidance for conducting Product Environmental Footprint assessments for rechargeable batteries has been recently published[10] (see **Box 3**).

LCA does carry various uncertainties; the models used do not capture the full picture in a number of ways, for instance, they simplify the industrial value chain from the mine to the battery, the emissions produced during each step of the value chain, and the environmental impacts of the emissions. Nonetheless, LCA serves as a useful tool to highlight 'hotspots' of potential environmental pressures, while also providing a general picture of overall environmental performance.

2.1 Material issues

A wide range of materials are used to make electrodes and electrolytes, which can present issues in relation to resource availability, toxicity, safety, production and recycling or disposal impacts. Electrode materials are particularly important to improving the environmental profile of batteries (Larcher and Tarascon, 2015).

2.1.1 Resource availability

Soaring demand for batteries, alongside the huge size of future energy storage installations, is going to increase pressure on material resources. It is generally accepted that there are sufficient reserves of most of the key constituents of batteries. However, their supply in raw form is clearly not endless and may one day become a problem unless action is taken.

This is particularly true for lithium-ion technologies, which are expected to meet an important part of near-term demand for batteries. Research suggests that there are enough reserves of most of the main ingredients of lithium-ion electrodes to meet a modest but foreseeable rise in demand over the next decade (e.g. 10 % share of electric vehicles in the global fleet), namely lithium, manganese, nickel and natural graphite (Olivetti *et al.*, 2017).

10. http://ec.europa.eu/environment/eussd/smgp/pdf/PEFCR_Batteries.pdf

BOX 1.

Lithium-ion: today's battery of choice

Lithium-ion technologies are the fastest growing form of battery on the worldwide market, with the potential to dominate the market in the short term. At the global and EU level, lead-acid technologies are expected to still prevail in 2025 in terms of volume, but the lithium-ion market is expected to become greater in terms of value from 2018 onwards.

Lithium-ion batteries have been used for some time in portable electronics, but they have recently become the technology of choice for e-mobility. Lithium cells developed for the e-mobility sector are, very often, also used in other applications – namely stationary energy applications – given the economies of scale this sector creates, although lower performance cells (for example, in terms of energy and power density) are also able to meet the needs of stationary applications.

Lithium-ion is not a single technology, but a family of technologies. Although they all rely on lithium as the shuttling ion (i.e. the ion that moves between cathode and anode), different versions of the technology combine the lithium with a variety of other materials to confer different properties.

Each type of lithium-ion battery is typically referred to as some form of abbreviation of its active cathode materials, for instance, Lithium Cobalt Oxide, one of the most common types (used in portable batteries, for instance), is called 'LCO', while Lithium Nickel Manganese Cobalt Oxide is named 'NMC' (increasingly used in mobility applications).

The use of lithium-ion batteries is expected to accelerate in the near future. Their design is likely to evolve during this time, but scientists believe that they may soon reach their performance limits, particularly in terms of their energy density. Thus, in addition to efforts to develop future evolutions of lithium-ion, the quest is now on to identify potential alternatives that offer better performance with an improved environmental profile.

However, despite available reserves, concerns remain surrounding the supply of battery materials, especially if there is a sharp increase in demand which pushes up market prices. Further, there are unlikely to be enough reserves of cobalt, and potentially lithium, for 100% electrification of the world's vehicle fleet under continuous growth conditions, extreme scenario calculations suggest (Weil, Ziemann and Peters, 2018, Vaalma *et al.*, 2018).

In addition, although lithium, manganese, nickel and natural graphite may currently have abundant deposits, they are mined in a very small selection of countries (primarily outside the EU), which creates potential supply risks (European Commission, 2018). Another important issue is the significant quantity of critical raw materials for the EU (defined as those which are both of high economic importance for the EU and have a high risk of supply disruption)[11] embedded in many battery technologies, such as antimony, cobalt, natural graphite, indium and some rare earth elements, depending on the battery's chemistry (Mathieux *et al.*, 2017).

11. http://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en

2.1.2 Environmental impacts

2.1.2.1 Electrode materials

Mineral extraction and metal refining represent the most important contributors, among life-cycle stages, towards the total environmental impacts incurred during the lifecycle of any type of battery.

In the case of lead production for batteries and sheets, it is estimated that the main contributors to environmental impact are mining and concentration, and smelting (Davidson, Binks and Gediga, 2016). In the case of lithium-ion batteries, the mining of some electrode materials, particularly cobalt (see **Box 2**) and nickel, significantly increases the environmental footprint of these batteries as reflected in LCAs, because toxic substances leak from mine tailings. It is also responsible for high levels of sulphur oxide emissions which are released during the smelting step of virgin cobalt and nickel recovery (Dunn *et al.*, 2015).

Cobalt and nickel are often mined in countries with less stringent environmental and health and safety regulations than in Europe. Significant social issues are also associated with cobalt mining, such as the use of child labour and dangerous working conditions (Tsurukawa, Prakash and Manhart, 2011). While there are significant uncertainties in available toxicity data, it can be agreed that efforts to minimise leakage of toxic substances from mine tailings will benefit the environmental performance of batteries (Nordelöf *et al.*, 2014).

12. https://www.ila-lead.org
13. https://echa.europa.eu/candidate-list-table

BOX 2.
Cobalt

Cobalt is a cathode material in lithium-ion batteries that needs addressing urgently. It has a risky supply chain, partly due to geopolitical issues. The majority (64%) of the world's cobalt is mined in the Democratic Republic of Congo, a politically instable country, as a by- or co-product of copper or nickel, and so its supply also depends on demand for these parent materials. There are notable industry efforts to lower the cobalt content of batteries, but if electric vehicles are to make up a significant share of the fleet, cobalt will remain in demand and risks associated with its supply will persist (Olivetti *et al.*, 2017).

Cobalt is important in giving lithium-ion batteries their high energy density and is, therefore, difficult to substitute. Cobalt-free cathodes are available, which are lower in energy density but are suitable for certain applications (see **Section 2.1.3.2**).

Increasing the efficiency in the use of the resources concerned, through recycling or re-using, is the most obvious way to reduce the impact of extractive activities. Lead may be considered a success story, in this respect. According to data from the International Lead Association[12], more secondary (recycled) lead than primary (raw) lead is used globally and within the EU. It should be noted, however, that the European Chemicals Agency (ECHA) recently added lead metal on to its Candidate List of Substances of Very High Concern (SVHCs)[13] due to its toxic properties, in addition to already listed lead compounds.

2.1.2.2 Electrolyte risks

The type of electrolyte used has a major impact on the performance of a battery, but a compromise may need to be reached between electrolyte performance and safety. Some substances used in electrolytes can potentially have negative impacts on human health. The sulphuric acid used in lead-acid batteries is a good example of this problem. However, lithium-ion batteries are not risk-free either. As well as being highly flammable, current lithium-ion electrolytes are potentially able to form a toxic atmosphere if accidentally released in a (semi-) enclosed space, such as a garage, tunnel (in the event of a car crash, for instance) or recycling facilities (Lebedeva and Boon-Brett, 2016). This is due to the solvents they use and the formation of hydrogen fluoride (HF), a highly toxic[14] and corrosive decomposition product of the lithium salt ($LiPF_6$) commonly used in the electrolytes. HF forms when the salt comes into contact with atmospheric moisture or traces of water.

2.1.2.3 Binders

Binders hold the components of the battery together. They are environmentally problematic because they are typically made of fluorinated substances, whose

production is energy-intensive and associated with the emission of ozone-depleting substances (Peters & Weil, 2017). Furthermore, they need volatile and toxic solvents for processing, are unsuitable for recycling and do not biodegrade (Richa, Babbitt, Gaustad, & Wang, 2014).

Binders also present some safety concerns: at high temperatures (for example, if a lithium-ion battery overheats or catches fire), together with lithium salts, they can contribute to the formation of HF (Larsson *et al.*, 2017).

2.1.3 Material issues: going forwards

An obvious means to reduce both our reliance on limited resources and the negative impacts of mining, no matter where extractive activities take place, is to increase the supply of secondary (recycled) raw materials. The way batteries are handled at their end-of-life also affects their toxicity; recycling and other forms of end-of-life treatment are discussed in detail in Section 2.4.

The development of higher density batteries, which need less material overall, is another means of reducing pressure on resources and the toxic impacts caused by their production. Likewise, the switch to more abundant, less harmful materials will also help ensure the better use of resources.

2.1.3.1 Energy density

Energy density is critical for portable electronics and e-mobility, where large, heavy batteries are impractical or undesirable. It is also of relative importance for stationary batteries in homes with limited space. These applications need as much energy as possible per unit of volume (measured in litres) and weight (measured in kg). Higher energy density also allows smaller, lighter batteries to be used in appliances, thereby also enabling smaller, lighter appliances. Additionally, a high density battery can work longer on single charging than a same-sized battery with lower density, meaning that the battery needs recharging less often – this is critical in extending the range of electric vehicles, for instance.

A higher density is also associated with lower production impacts; for a low-energy-density battery, a greater amount of battery is needed to provide the same amount of energy, increasing the impacts accordingly.

Battery	Advanced lead-acid	Sodium-sulphur	Sodium-nickel-chlorine	Lithium-ion	Redox flow
Energy density (Wh/kg)	25-50	120-150	95-120	100-200	10-50

Table 1. Gravimetric energy density (Wh/kg) of main battery technologies used for energy storage.
Adapted from: Alotto, Guarnieri and Moro (2014).

14. https://emergency.cdc.gov/agent/hydrofluoricacid/basics/facts.asp

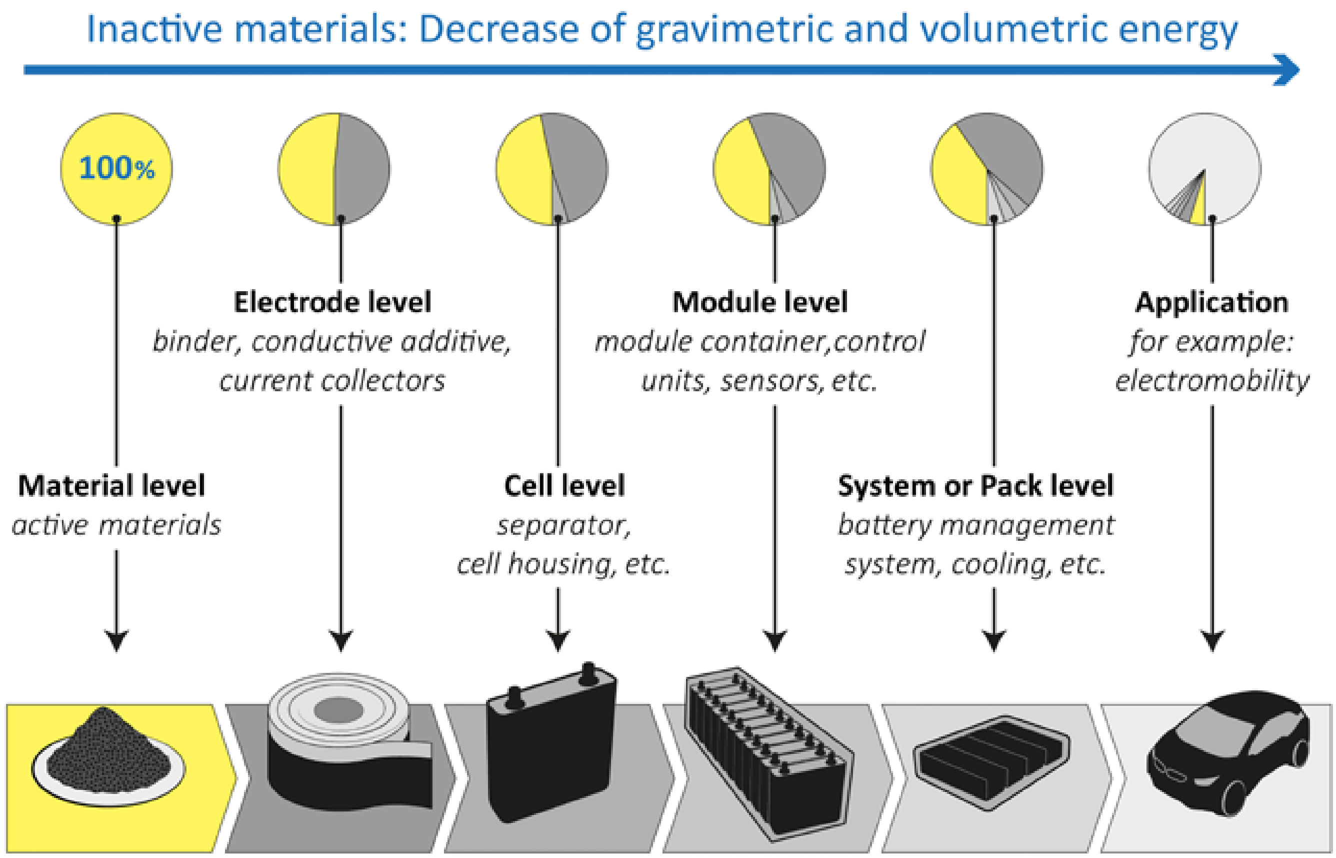


Figure 2. Schematic illustration of a battery's production chain, from the material level via the battery cell, to the battery system level. In each step, inactive components are added and assembled into a key 'building block' for the battery system, which 'dilute' the energy provided by the active materials.

In assessing energy density, it is important to consider each step in a battery's production chain, that is, the process of assembling parts for the complete battery system, including peripheral components, such as the battery management system (Placke *et al.*, 2017). The chain begins with the 'active' materials used in the anodes and cathodes, which give the battery its source of energy through chemical reactions. Each additional 'inactive' component, such as binder (see **Section 2.1.2.3**) or housing system, added to the battery 'dilutes' the energy density in the process of achieving the final battery (see **Figure 2**). While the weight and volume of these inactive components must be minimal for a maximum energy output, certain inactive materials or minimum amounts are essential to ensure key performance and safety requirements. Studies often report on the energy density of new battery technologies based on laboratory tests on the active materials alone. It is challenging to predict what the energy density of those technologies will be if and when they eventually come into commercial use. For more realistic projections of density, it is important to predict the effects of the wider battery pack or system on density (Berg *et al.*, 2015), while also recognising that these predictions carry uncertainties.

There is a limit to the effects of active materials' chemistry on energy density. Thus, further improvements are needed to inactive cell material components, which reduce the weight and volume, as well as changes in how the whole battery is engineered and organised on a system level (Placke *et al.*, 2017).

2.1.3.2 Alternative materials

Future cathode materials: examples

In conjunction with the pursuit of greater energy density, scientists are also exploring technologies which use more plentiful and/or safer cathode materials. The following examples of developing technologies briefly illustrate the use of some of these materials in relation to their abundance, toxicity and energy density:

- **Lithium-sulphur.** These are considered one of the most promising next-generation batteries for electric vehicles. While they still contain lithium, they avoid nickel and cobalt. Further, they use sulphur in the cathode which is cheap and abundant. calculate that the toxic impacts of a lithium-sulphur battery are 22% lower than for a standard lithium-ion battery (NMC111), mainly because they avoid nickel and cobalt mining and production activities. However, lithium-sulphur batteries currently have low volumetric energy density (i.e. they are lightweight but big).

- **Lithium-air.** These use oxygen, an unlimited resource, for the positive electrode. In theory they could reach energy densities ten times greater than most batteries currently on the market, based on assessments of their active materials alone. However, at a system level, they are likely to require significant peripheral components to avoid the pure oxygen degrading in ambient air, such as oxygen tanks or air separation units, which, in practice, would drastically reduce their energy density (Gallagher *et al.*, 2014).

- **Sodium-ion.** This is '*without a doubt the most appealing alternative to lithium-based battery technology, from the viewpoint of sustainability*' (Grey and Tarascon, 2017). It contains no lithium, and sodium is an abundant resource that is not associated with any geopolitical issues. It is less energy dense than lithium-ion, but progress is expected and it has good potential for stationary energy storage systems where weight and volume are less critical. This chemistry could also have potential to meet transport sector needs in the long run, according to the European SET-plan on Batteries (see **Introduction**). Its current lower energy density does increase demand for other components for providing the same storage capacity, however. In a LCA study, evaluated that, overall, sodium-ion batteries have fewer toxic impacts than lithium-ion batteries.

It should be noted that these technologies are not yet ready for market application and significant research efforts are needed, in particular to address safety issues, long-term quality and their lifespan.

Moreover, material abundance, energy density and toxicity clearly form only part of the environmental picture. For example, although lithium-sulphur batteries may be less toxic than lithium-ion batteries, when a wider range of environmental impacts are considered (e.g. GHG emissions), they are unlikely to be more environmentally friendly overall than lithium-ion batteries. This is owing in part to more energy-intensive production processes and solvents needed to manufacture the cathode (Cerdas *et al.* 2018). Purifying oxygen for lithium-air batteries is similarly energy-intensive (Larcher and Tarascon, 2015; Grey and Tarascon, 2017).

Non-fluorinated binders

Greener alternatives to fluorinated binders are in development and use (to some extent). Carboxymethylcellulose is a promising alternative in terms of ensuring good performance of lithium-ion batteries, while also being much cheaper than conventional binders, such as polyvinylidene fluoride. It is made of cellulose, which is derived from plants and is thus renewable, and is water-soluble – so toxic solvents are not needed. Studies have found it to have comparable, or even superior, performance to conventional binders in lithium-ion batteries (Jeong *et al.*, 2012; Mancini *et al.*, 2011). It is already successfully used in lithium-ion anodes, but is not suitable for all technologies as some electrodes are moisture sensitive or water soluble (Larcher and Tarascon, 2015). It is also, at present, unsuitable for cathodes, however, there is promising research to indicate that it will probably become feasible in future (Chen *et al.*, 2017).

Cobalt substitution

Lithium-ion battery manufacturers are gradually reducing the cobalt content of cathodes. Non-cobalt-containing cathodes, such as manganese spinels (LMO) and lithium-iron-phosphate (LFP), are also available. They have a lower energy density, but are attractive for some applications. For instance, the high stability and high power capability of LFP makes it a contender for large scale applications, such as those in electric grids. At present, some consider LFP the most attractive electrode material, sustainability-wise (Larcher and Tarascon, 2015).

2.2 Energy issues: production and charging

2.2.1 Source of energy for production

The carbon-intensity of energy used to manufacture batteries has a significant impact on their environmental footprint. Lithium-ion battery production is very energy-intensive and involves a series of complicated manufacturing processes, including cell assembly in severe dry room conditions, with extremely low humidity, in order to avoid the formation of HF (see **Section 2.1.2.2**)

Around 328 Wh of energy is needed to produce just 1 Wh of lithium-ion battery capacity – this is the average figure taken from 19 studies which assessed cumulative energy demand for seven types of lithium-ion battery (Peters *et al.*, 2017). The total mean GHG emissions associated with the production of 1 Wh of storage capacity are 110 g of CO_2eq, according to same review.

Lithium-ion batteries are usually manufactured in Asian countries with an electricity mix that is different to most European countries. It is possible to compare the GHG emissions of manufacturing batteries based on different energy sources. Thus, for instance, NMC lithium-ion cells for electric vehicles that are currently manufactured in South Korea, which has an energy mix dominated by coal, nuclear and gas, have a global warming potential that is 60% higher than if they were produced with a 100% hydropower-based electricity supply (Ellingsen *et al.*, 2014).

15. https://www.wired.com/story/ev-green-battery-factory-in-the-netherlands-competes-with-the-gigafactory/

The most efficient way of reducing GHG emissions from the production of batteries is to manufacture cells in facilities powered entirely by renewable energy sources (Ellingsen, Hung and Strømman, 2017). Promisingly, there are some notable new 'gigafactories' (large battery factories) in development, including what is reported to be Europe's largest battery factory when it is fully running in 2023 in Sweden, which is expected to be powered by hydroelectricity[15].

Although emissions vary according to the local source of energy for the production plant, in the long term it can be expected that emissions will fall with increased adoption of renewable sources of energy and the development of new and cleaner technologies.

2.2.2 Roundtrip efficiency

'Roundtrip efficiency' refers to the amount of energy that comes out during discharge of a secondary battery (e.g. when it is used to power an appliance), compared with how much was put in to charge it. The battery loses some energy during each one of these charging cycles. A higher roundtrip efficiency means that less energy is lost during these cycles, which lowers the environmental impact associated with the production of energy used for charging, such as GHG emissions from fossil fuel combustion. In addition, by reducing the loss of waste heat, a high roundtrip efficiency can lead to increased energy density (see **Section 2.1.3.1**) of the whole battery system, because it reduces the size of auxiliary equipment used for cooling.

Typical lead-acid batteries have an efficiency over 70-80% (Reddy, 2010), i.e. 20-30% of energy is lost during charging cycles. Lithium-ion batteries are very efficient, at over 90%. Over a battery's lifetime, a 10% loss is still responsible for some significant environmental impacts, however, which can be as great as the impacts of production of the battery itself, in terms of energy demand and GHG emissions. The internal inefficiencies for every 1 kWh of electricity stored in the battery cause 0.3 kWh of energy demand and emissions of 46.7 g CO_2eq, assuming an average European electricity mix for 2012 (Peters *et al.,* 2017).

Small efficiency improvements can lead to sizeable environmental gains. For instance, just a 2% improvement in efficiency, from 90% to 92%, would lead to a 7% reduction across a range of environmental impacts associated with producing the electricity used to charge batteries (assuming a European electricity mix). These include potential toxic impacts of pollutants on humans, eutrophication of marine and fresh waters, and impacts of acidifying pollutants on ecosystems (Peters *et al.,* 2016).

Although roundtrip efficiency is important, it should be noted that it can come with trade-offs. In the case of vanadium redox flow batteries, for instance, (see **Case Study 2**), additional materials or energy inputs may be needed to increase efficiency, such as adding sulphuric acid to reduce internal resistance (Arbabzadeh *et al.,* 2016).

As with manufacturing, the energy source used to charge secondary batteries – whether carbon-intensive or low-carbon – will strongly influence the environmental impacts of battery usage. It can be expected that these impacts will fall per unit of output in the future as the share of renewable energy in the electricity mix increases in concurrence with ongoing battery development for energy storage.

2.3 Lifespan

A long battery lifespan reduces the number of times that a battery needs to be replaced. This is particularly critical for usage in energy storage and electric vehicles, which have longer lifespans than most portable electronics. As well as reducing costs, a long lifespan reduces pressures on resources and any negative impacts of both manufacturing and recycling, such as energy consumption. In addition, it can extend the use of the device in which the battery is placed, for instance, it may reduce instances of consumers discarding working smartphones due to battery End-of-Life (EoL).

A battery's lifespan can be measured in two ways:
1.) in terms of 'calendar years', which is the length of time a battery can be stored with minimal discharges before its capacity diminishes, and
2.) in terms of its 'cycle life', that is, the number of times it can be recharged and discharged before it becomes unsuitable for a given application. This is usually when it can only be charged up to 80% of initial capacity, given that the battery degrades quickly after this point.

In reducing environmental impact, increasing lifespan is one of the most important aspects of battery design to focus on when developing alternatives to lithium-ion batteries. This can be illustrated using the example of sodium-ion batteries, an emerging technology (**see Section 2.1.3.2**). Their cycle life is not yet clear, but at 2000 cycles, they would be environmentally comparable to a number of lithium-ion batteries per kWh of storage capacity. At 3000 cycles, however, they would be environmentally superior to nearly all lithium-ion batteries, with the exception of the LFP–LTO type (LFP cathode and LTO anode) which has an exceptionally high cycle life of 13,850 (Peters *et al.,* 2016).

New *'in situ'* methods to monitor batteries in operation for signs of degradation, i.e. monitoring systems within a battery itself, could provide information that helps extend the lifespan of batteries in several ways (Grey and Tarascon, 2017). Firstly, improved monitoring could provide

insights that inform the design of new materials and improvements to existing technologies. Monitoring could also be used to perform a 'health check' on batteries in use: sensors inside a cell could transmit information on battery faults to the 'outside world' through an optical fibre, allowing the fault to be repaired. This 'health check' could also support a market for second-hand batteries, by verifying the history of each battery and allowing appropriate pricing and insurance as it enters new applications. It should be noted, however, that these monitoring systems are likely to come with trade-offs, such as increased demand for materials or additional recycling challenges.

2.4 End-of-Life (EoL) treatment

Circular economy End-of-Life (EoL) approaches, such as re-use and recycling, provide a number of environmental benefits. Recycling provides a secure and domestic source of secondary raw materials, and reduces environmental impacts associated with extracting raw materials, such as GHG emissions and the ecological and toxic impacts of mining. By increasing the lifespan of batteries, re-using can contribute to a more efficient use of resources.

2.4.1 Recycling

In addition to increasing the efficiency in the use of resources, recycling provides direct environmental benefits. For instance, the GHG emissions of an LMO lithium-ion battery could be reduced by up to 50% over its lifetime if it used recycled cathode, aluminium, and copper instead of entirely virgin materials (Dunn *et al.,* 2012). Moreover, recycling LCO batteries results in a reduction in SO_x emissions by almost 100%, largely because it avoids the SO_x-intensive smelting step of virgin cobalt recovery (Dunn *et al.,* 2015).

Although no official data are reported to the European Commission, it can be stated that the level of recycling of lead-acid automotive batteries within the EU is very high[16]. Several factors explain this high level. Lead-acid batteries are relatively simple products, with few materials and a basic design that is standardised across the market. In addition, a well-established professional network ensures high levels of collection of spent batteries, which lowers costs and increases benefits for recyclers.

Conversely, recycling lithium-ion batteries is technologically challenging, for many reasons. They contain a large number of blended materials, which makes recycling more complex than for simpler technologies like lead-acid, and a battery pack for an electric vehicle or energy storage is likely to contain 100 or more individual cells. The array of chemical compositions for the electrodes, which vary by manufacturer and battery function, adds a further complication, especially as the composition is not labelled for the recycler's information. It is difficult for recycling companies to adapt to the continually evolving composition of electrodes, which may never standardise (Gaines, 2014; Heelan *et al.,* 2016). Moreover, the two main methods of recycling for lithium-ion batteries are energy intensive.

Spent lithium-ion batteries are a pressing concern, given their high number. Globally, it is predicted that there will be over 25 billion by just 2020, driven largely by the rise in electric vehicles (Zeng, Li and Singh, 2014). Within the EU, these batteries cannot be landfilled as they leach substances that are potentially toxic and can also explode. Likewise, they cannot be incinerated as the ashes remain toxic in landfill (Winslow, Laux and Townend, 2018).

16. EUROBAT estimates it at 99.5 %: http://www.eurobat.org/environment-health-safety/recycling

In most cases, recycling of waste lithium-ion batteries is geared towards recovering cobalt, nickel and copper, as these are considered to be the most economically valuable substances. The materials are then only partially recovered (Sonoc, Jeswiet and Soo, 2015; Peters and Weil, 2017). Most other substances contained in the battery are not recovered, even where it is technically possible to do so (European Commission, 2018). Thus, for instance, lithium usually ends up in the slags of recycling processes which are used as construction materials. The declining use of cobalt in lithium-ion batteries is to be applauded (see **Box 2**), but concerns remain that recycling lithium-ion batteries could become economically unattractive without cobalt recovery. No doubt triggered by demand forecasts and the rising prices of lithium, however, the recycling of lithium from waste batteries is expected to start soon in the EU[17].

2.4.2 Re-use

Re-use is an important EoL option that could support a circular economy and lower batteries' environmental impacts by increasing their lifespan (see **Section 2.3**). Batteries from electric vehicles that have lost their initial capacities (i.e. have reached 75-80% of initial capacity) may still be used in other, less demanding, applications, particularly stationary energy storage after being disassembled and refurbished (Richa, Babbitt and Gaustad, 2017).

There is still much to learn about how batteries perform and age in 'second life' applications. Some pilot projects and studies conclude that second use is technically feasible for lithium-ion batteries and that some economic and environmental benefits could occur (Heymans *et al.,* 2014; Bobba *et al.,* 2018). Research also indicates that they undergo multiple and complex physical and chemical processes in these new uses, which vary according to operating conditions. Therefore, one of the main challenges for re-using ex-electric vehicle lithium-ion batteries is to design a battery management system that can measure and quantify the evolution of performance, and to use this information to accurately predict a battery's remaining useful life for a given application (Podias *et al.,* 2018).

It is also possible to disassemble and then reprocess an EoL battery to its original manufacturer specifications. This involves thoroughly inspecting and cleaning each component (Ramoni and Zhang, 2013). Another option for spent lithium-ion batteries may be refunctionalisation of cathodes, e.g. through lithiation, a chemical process which restores lithium content to cathodes (Ganter *et al.,* 2014).

2.4.3 Design for recycling and re-use

Design principles that make batteries safe and convenient to disassemble could help avoid the pitfalls associated with recycling lithium-ion technologies, and encourage their re-use.

A number of possible options are available here: designs that allow easy separation of parts, reversible joining (nuts and bolts instead of welding), labels for parts, using a minimum number of materials and components, standardising formats and materials, allowing easy removal of the battery from the device (e.g. the electric vehicle), and minimising use of hazardous materials. Ideally, the batteries of a given type should be as uniform as possible (Gaines, 2014; Arbabzadeh *et al.,* 2016; Ramoni and Zhang, 2013; Richa, Babbitt and Gaustad, 2017; Ahmadi *et al.,* 2014).

17. https://uk.reuters.com/article/us-umicore-recycling/belgiums-umicore-plans-to-ramp-up-ev-battery-recycling-capacity-ceo-idUKKBN1KN1ZO

'Design for disassembly' requires a major change in the way batteries are developed, as its principles need to be incorporated early on in a new technology's development. As Heelan *et al.* (2016) write: *"At present, we are addressing recovery and recycling as an afterthought. The closed-loop mindset and manufacturing for disassembly should be considerations from day one."*

BOX 3.

Harmonised environmental footprinting for rechargeable batteries

The European Commission has published a method for calculating the product environmental footprint (PEF) of High Specific Energy Rechargeable Batteries for Mobile Applications. This PEF provides credible information to consumers and investors on batteries' environmental performance and can be used across international borders.

The PEF is specifically applicable to lithium-ion and nickel-metal hydride (NiMH) batteries used in cordless power tools, ICT and e-mobility. It is based on Life Cycle Assessment and was developed using the PEF method adopted by the European Commission in 2013[18]. It covers environmental impacts throughout the battery's value chain, from the extraction of resources to the end-of-life of the product, and measures performance across 16 impact categories[19].

It was developed as part of a series of methods for a range of products and organisations to create a level playing field in the EU for companies wishing to compete on the basis of environmental performance. The application of the PEF/OEF (Organisation Environmental Footprints) methods leads to results that are more reliable, reproducible, comparable and verifiable. They can be used by companies to better manage their supply chain, but also to better communicate the environmental performance of their products to their stakeholders.

These PEFs and OEFs are designed to help overcome consumer and investor mistrust in many of the green claims made by the vast, confusing array of environmental labels. There are more than 463 environmental labels worldwide[20], a minority of these labels are credible, whilst the vast majority are not. Furthermore, companies who use environmental labels face the cost of using different methods for different markets.

18. 2013/179/EU: Commission Recommendation of 9 April 2013 on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32013H0179
19. Climate change, ozone depletion, human toxicity – cancer effects, human toxicity – non-cancer effects, particulate matter, ionizing radiation, photochemical ozone formation, acidification, eutrophication – terrestrial, eutrophication – freshwater, eutrophication – marine, ecotoxicity – freshwater, land use, resource depletion – water, resource depletion – mineral, fossil.
20. Ecolabel Index, accessed August 2018: http://www.ecolabelindex.com/ and Opportunities in Europe for Environmental labels: http://ec.europa.eu/environment/eussd/smgp/pdf/2017_Euromonitor_EU_opp_envlabels.pdf

BOX 3. – continued

Harmonised environmental footprinting for rechargeable batteries

A four-year pilot phase tested the product- and sector-specific calculation rules for the footprints (Product Environmental Footprint Category Rules – PEFCRs and Organisation Environmental Footprint Sector Rules – OEFSRs, respectively). Among the main achievements of the pilot phase are:

- The development of a ‘benchmark’ for each product category. The benchmark is the quantified environmental performance of the average product sold in the EU on all the impact categories.
- Identification of the most relevant impacts, life cycle stages and processes: typically there is a limited number of processes (10-20) that drive the environmental performance of the product or sector.
- 5000 datasets available for free to those applying the PEFCRs and OEFSRs developed during the pilot phase, with 3000 more to come in the near future.
-
- An important reduction of costs, compared to similar assessment, in the range of 80-90%.

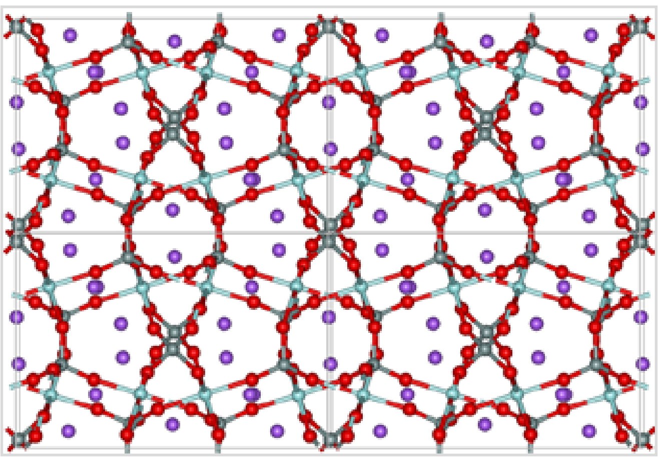
The results of the pilot phase, including for rechargeable batteries, are available at http://ec.europa.eu/environment/eussd/smgp/PEFCR_OEFSR_en.htm

Section 3. Case studies

There are a large number of battery technologies in development, designed to address various problems with existing technologies and to create new opportunities for batteries in energy management, cleaner mobility and the expansion of the digital society. Some examples of these are discussed briefly in Section 2.1.3.2, namely lithium-sulphur, lithium-air and sodium-ion, which all use alternative cathode materials.

This section takes an in-depth look at three further emerging technologies: solid-state lithium, redox flow and printed. It discusses their design, applications, performance and environmental characteristics.

As these technologies are still in development, environmental assessments are lacking and information on performance is often preliminary. These case studies, therefore, provide an indicative picture using available data, speculations and information inferred from related technologies. They nonetheless help illustrate their potential as well as the challenges of optimising performance while balancing the varied facets of environmental sustainability.



The crystal structure of a NASICON solid electrolyte, considered one of the most promising types owing to its overall performance in ionic conductivity and chemical and electrochemical stability, according to (Zheng *et al.*, 2018)

Case study 1: Solid-state lithium

Next-generation lithium-ion

Solid-state lithium batteries (a form of lithium-ion battery) are often considered to represent the next big leap in battery technologies, and are likely to be in use in the foreseeable future. They are potentially suited for a large variety of applications: energy storage, electric vehicles and portable electronics. They could be the first battery technology which ensures the needed leap in energy and power density increase, as well as safety.

Like other members of the lithium-ion family, numerous chemical technologies can be used for the electrodes. Unlike conventional lithium-ion batteries, however, which have a liquid electrolyte, this version has a solid electrolyte, usually made of a ceramic (inorganic electrolyte) or a polymer (organic electrolyte).

Solid-state batteries promise a longer lifespan and much greater safety than liquid electrolyte technologies, which are flammable. The solid electrolyte also allows for different electrode materials, notably, lithium metal can be used as the anode material, instead of carbon/silicon typically used in current lithium-ion batteries. This could lead to a 70% increase in volumetric energy density, compared with those that use conventional anode materials, plus a better cycle life, lower weight and lower cost (Schnell *et al.,* 2018; Motavalli, 2015). One recently reported design claims to actually increase its capacity over time, and have a very high lifespan of 23,000 cycles (Braga *et al.*, 2018).

Commercialisation of solid-state lithium batteries is at least a decade away. To further develop this technology and bring it into widespread use, it is important to improve the interface between the electrolyte and the electrodes to increase power (Zheng *et al.*,2018).

In terms of environmental performance, early indications suggest that their manufacture has lower environmental impact than for conventional lithium-ion batteries. For instance, a lifecycle analysis (excluding EoL) of solid-state and conventional lithium-ion batteries for electric vehicles concluded that the solid-state versions had 25-65% lower impacts on energy demand and GHG emissions, per unit of energy storage (Lastoskie and Dai, 2015).

These environmental benefits largely arise from the simpler production processes for solid-state batteries. In particular, they do not need the complex, energy-intensive 'lamination' process for making cathodes, as required by those with liquid electrolytes. Instead, solid-state batteries can use 'thin film' cathodes, which are easier and less energy-intensive to manufacture. Thin-film cathodes also require fewer solvents, which lowers toxicity impacts.

It is possible to speculate, to some extent, on the EoL treatment of solid-state batteries. For example, it is known that ceramic electrolytes are usually doped with some (comparably rare) transition metals, such as indium or germanium, but ceramic electrolytes are difficult to recycle. Recovering the metals from the ceramics would require extremely high temperatures and is probably not feasible. Solid electrolytes made from organic materials do not have this problem, but would probably be oxidised or burned in the recycling process, lowering the recovery efficiency (Peters, 2018, in correspondence). As with other lithium-ion batteries, the highly integrated and variable composition of their electrodes present recycling challenges.

Case study 2: Redox flow batteries

Flexible energy storage in tanks

Redox flow batteries are well suited for stationary energy storage. They can store energy for a long time and release it quickly when needed. They are durable, with a long lifespan (in terms of both cycle life and calendar life), efficient, and have reasonable capital costs. They could one day replace lithium-ion batteries as the predominant energy storage battery technology for stationary applications (Weber *et al.*, 2011; Savage, 2015).

Redox flow batteries © Application Center Redox-Flow at the Fraunhofer Institute for Chemical Technology ICT

Flow batteries store energy in the electrolyte, unlike conventional batteries which store energy in the electrodes. The liquid electrolyte contains a dissolved energy-storing material (a metal or a polymer); the most common and advanced electrolyte for this technology uses the metal vanadium dissolved in acid as vanadium pentoxide (V_2O_5).

The electrolyte is stored in two external tanks, one positive and one negative, and is pumped through a stack of cells where an electrochemical reaction occurs. One of redox flow batteries' key advantages is that they separate power (in the stack) from the energy (in the electrolyte), also unlike conventional batteries. Power and energy are thus controlled separately, allowing for a flexible design that can be easily tailored to individual requirements, and scaled up or down in size without losing power density (Leung *et al.,* 2017).

Their energy density and efficiency is lower than for lithium-ion batteries intended for the same purpose, but their cycle life is much higher (**see Table 2**). However, energy density is not as critical for stationary energy storage as it is for vehicles or portable/consumer electronics where size is far more paramount.

compared with many other stationary energy storage batteries, including a number of lithium-ion technologies (LFP, LMO, NCM, NCA (115-168 kg CO_2/kWh)). This is due to vanadium redox flow batteries' low energy density, low efficiency, and the carbon-intensity of vanadium production.

However, this study did not account for the EoL stage of a battery's life. Redox flow batteries can be seen as a model for recyclability. According to Peters *et al.* (2018), the environmental benefits incurred by the high recyclability of vanadium redox flow batteries could outweigh the negative impacts of their production and low density. Their simple and flexible design makes them much easier to recycle than lithium-ion as each component can be independently removed and replaced. The vanadium can be recovered almost entirely and recycled 10-20 times, or more. In theory, these batteries can last over 20 years (compared with around 10 years for lithium-ion); this long lifespan relieves pressure on material resources and reduces production impacts.

	Vanadium redox flow	Lithium-ion (LFP-LTO)	Lithium-ion (LFP-C)
Energy density (Wh/kg)	25.8	37.8	57.6
Cycle life (cycles)	>10,000	7500	2500
Efficiency (%)	75	93	96

Table 2 Key performance characteristics of vanadium redox flow batteries compared with two types of lithium-ion technologies for stationary energy storage. Adapted from: Peters, Baumann and Weil (2018)

On the basis of limited available data, Baumann *et al.* (2017) conclude that vanadium redox flow batteries have a high carbon footprint at 183 kg of CO_2 per kWh of energy stored, over their lifetime,

Vanadium is a critical raw material also used by the steel industry which is environmentally toxic if improperly handled at EoL (Deutz *et al.,* 2017). The limited availability and high cost of such metals

are barriers to flow batteries' widespread adoption (Huskinson *et al.,* 2014). Non-metal alternatives using organic molecules, which are far more plentiful, are in development, however. Quinones, which are compounds found in plants, fungi and bacteria, appear to be a low-cost and abundant option worthy of further exploration. Research is ongoing to enable redox flow batteries to reach their full commercial potential through cost and size reductions with better energy density in order to compete with lithium-ion. Future high-density systems may also be suitable for powering electric vehicles (Alotto, Guarnieri and Moro, 2014).

BOX 4.

Molten-salt batteries

One form of energy storage which warrants mention is **molten-salt**, or **high-temperature sodium** batteries. These are not a new technology, but are receiving much renewed attention and appear to have a promising environmental performance.

There are two main types: sodium-sulphur (Na-S) and sodium-nickel-chloride (NaNiCl). Na-S have reasonable energy density (150–240 Wh/kg), are low cost and make use of abundant raw materials. They have an efficiency of 80% and a lifespan of 15 years after 4500 cycles. They produce no emissions during operation and more than 99% of the overall weight of the battery materials can be recycled (the steel, copper and aluminium). Recycling sodium and sulphur remains a challenge, however. There are also safety concerns around Na-S following a major fire incident in 2011 in Japan, although the manufacturer reports increased safety measures since[21].

NaNiCl, better known as ZEBRA batteries, are safer than Na-S and their efficiency can match lithium-ion's, at up to 90%. Their energy density is relatively low, however (120 Wh/kg). As well as grid storage, they could be suitable for electric and hybrid vehicles.

The major drawback for molten-salt technologies is that they need to operate at a high temperature (300-350 °C). The battery's own stored energy is used as a heat source, but this reduces performance. Lower-temperature versions are in development (Xin *et al.*, 2014; Chen *et al.,* 2009).

21. https://www.ngk-insulators.com/en/news/20120425_9322.html

Case study 3: Printed batteries

Flexible and flat for small-scale devices

Printed batteries, also known as flexible batteries, can be thinner than a millimetre, weigh less than a gram and stretchable. They can supply power at the microwatt level, and are well suited for small devices, such as smart cards, sensors, RFID tags (for electronic identification), medical devices and wearables, such as wristbands. Their innovative format opens up opportunities for a new generation of electronics, including electronic labels, packaging and posters (Oliveira, Costa and Lanceros-Méndez, 2018) and could help drive the 'internet of things', the network of devices and everyday objects which are connected up to the internet and powered by small batteries.

Whilst their format may be innovative, printed batteries use existing chemical technologies, such as lithium-ion. They can, therefore, be rechargeable or non-rechargeable depending on the materials used. They are typically made of two sheets of a thin flexible material (the 'substrate'), such as paper, plastic or textiles, with the electrodes and electrolyte sandwiched in-between the sheets. These components are printed on to the substrate as ink (Oliveira, Costa and Lanceros-Méndez, 2018). Alternatively, the substrate itself can act as an electrolyte (if it is soaked in water, for example), placed in-between the anode and cathode (**see Figure 3**) (Nguyen, Fraiwan and Choi, 2014).

Printed batteries are already on the market. The main commercially available printed batteries are non-rechargeable and based on zinc-manganese dioxide, printed on plastic substrates with a voltage of over 1.6 volts (Oliveira, Costa and Lanceros-Méndez, 2018). These are used in a variety of applications including wearables for monitoring (e.g. for medical or sports performance purposes), and electronic tags and cards.

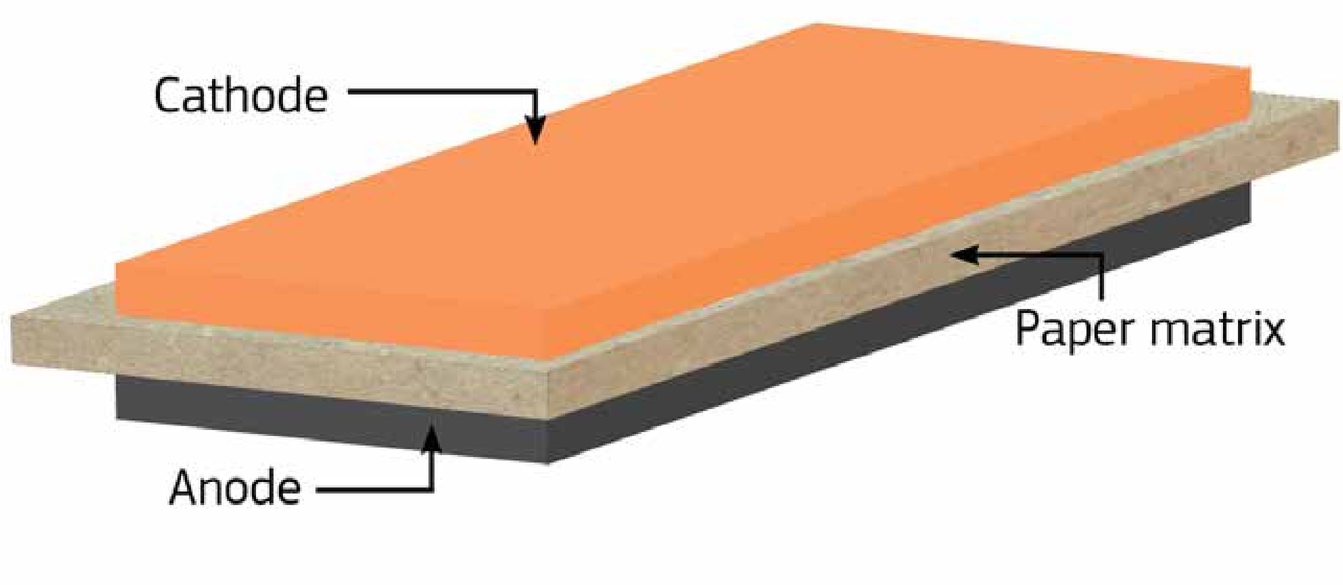


Figure 3. Diagram of printed battery with paper functioning as electrolyte. Adapted and redrawn from Nguyen, Fraiwan and Choi, 2014.

Printed batteries should eventually become more commercially competitive as production volumes increase, they become more cost-effective and the technology improves. The main challenge in their development lies with the inks. These need to be made more suitable for print processes, such ink-jet or screen printing, with the desired flow, adhesion and structure. To improve the battery's performance, the inks also need to have better ionic conductivity, mechanical and thermal qualities (Oliveira, Costa and Lanceros-Méndez, 2018).

Flexen printed battery © University of Cambridge

While environmental assessments are lacking for this technology, indications and speculations are possible. Individually, their material consumption is very small and efficient; printing is a simple, 'additive' manufacturing process whereby only as much material as is needed is applied to the substrate. More conventional and complex 'subtractive' processes use more energy and chemicals to remove excess material (which becomes waste) from components (Kunnari *et al.,* 2009). Paper substrates also represent a renewable, degradable and recyclable resource (Sharifi *et al.,* 2015).

However, the future proliferation of printed batteries presents an environmental concern; billions of batteries will be required to operate the internet of things, for example, and will pose a significant environmental risk if they are not correctly disposed of after use (The Royal Society, 2017).

Their EoL treatment presents several challenges (Keskinen and Valkama, 2009 – discussing orinted electronics more widely). Re-use of printed batteries is unlikely, as they are planned to be used in low-cost, often disposable, products with a short lifespan that consumers are unlikely to consider as e-waste. Recycling is also an issue; as with conventional lithium-ion batteries, for example, the materials are highly integrated. Using fewer materials would lessen this challenge.

They are also likely to be embedded within products and difficult to separate out for re-use or recycling; again, design for disassembly principles (see **Section 2.4.3**) could help overcome this issue. Aliaga *et al.* (2015)indicate that it is possible to recycle paper products that contain printed batteries, and remove the batteries by sieving them out of pulped paper in the recycling plant. However, in Aliaga *et al*'s small-scale experiment, the batteries were partially disintegrated following paper pulping and particles of their components were judged likely to reduce the recycled paper's quality. Landfilling of printed batteries is also likely to be problematic due to leaching of hazardous substances (Keskinen and Valkama, 2009).

Summary

Future batteries will play a key role in enabling a green and secure energy supply for Europe. Their development can support jobs and growth in key industries for the EU, including battery manufacturing itself, but also the automotive, energy and digital technology sectors. The pursuit of commercially competitive, high-performance batteries needs to go hand-in-hand with the quest to lower their environmental impact.

Numerous opportunities exist to tackle a range of environmental pressures currently exerted by batteries and some possible options are discussed in this report. These include: using non-toxic, abundant materials; increasing energy density; powering battery plants with clean sources of energy; extending battery lifespan; improving charging efficiency ('roundtrip efficiency') and enabling ease of recycling and re-use at end-of-life by embracing 'design for disassembly' principles.

These changes in design and production could bring about substantial environmental benefits: more efficient use of raw materials, reduced impacts of pollutants (from battery materials and electricity production) on human health and nature, plus fewer GHG emissions and lower energy consumption associated with the manufacture and use of batteries.

It remains challenging, if not impossible, to meet the wide set of performance and environmental criteria often expected of batteries. The choice of battery for a given application will always involve some degree of compromise and it is, therefore, important to select the most appropriate battery for a specific purpose.

Many exciting developments are taking place in the ongoing evolution of batteries. This report explores three forms of emerging battery technology in some depth: solid-state lithium batteries, redox flow batteries and printed batteries. These case studies illustrate their potential in helping meet the future needs of our society and opening up new commercial opportunities. They also demonstrate the challenges of optimising performance while balancing the varied facets of environmental sustainability.

References

Ahmadi, L., Yip, A., Fowler, M., Young, S.B. and Fraser, R.A. (2014) Environmental feasibility of re-use of electric vehicle batteries. *Sustainable Energy Technologies and Assessments*. 6 pp. 64–74.

Aliaga, C., Zhang, H., Dobon, A., Hortal, M. and Beneventi, D. (2015) The influence of printed electronics on the recyclability of paper: A case study for smart envelopes in courier and postal services. *Waste Management*. 38 pp. 41–48.

Alotto, P., Guarnieri, M. and Moro, F. (2014) Redox flow batteries for the storage of renewable energy: A review. *Renewable and Sustainable Energy Reviews*. 29 pp. 325–335.

Arbabzadeh, M., Johnson, J.X., Keoleian, G.A., Rasmussen, P.G. and Thompson, L.T. (2016) Twelve Principles for Green Energy Storage in Grid Applications. *Environmental Science & Technology*. 50 (2), pp. 1046–1055.

Avicenne Energy (2017) *Worldwide Rechargeable Battery Market 2016-2025 – 2017 edition*. Available from: http://www.avicenne.com/reports_energy.php.

Baumann, M., Peters, J.F., Weil, M. and Grunwald, A. (2017) CO 2 Footprint and Life-Cycle Costs of Electrochemical Energy Storage for Stationary Grid Applications. *Energy Technology*. 5 (7), pp. 1071–1083.

Bobba, S., Mathieux, F., Ardente, F., Blengini, G.A., Cusenza, M.A., Podias, A. and Pfrang, A. (2018) Life Cycle Assessment of repurposed electric vehicle batteries: an adapted method based on modelling energy flows. *Journal of Energy Storage*. 19 pp. 213–225.

Braga, M.H., M Subramaniyam, C., Murchison, A.J. and Goodenough, J.B. (2018) Nontraditional, Safe, High Voltage Rechargeable Cells of Long Cycle Life. *Journal of the American Chemical Society*. 140 (20), pp. 6343–6352.

Cerdas, F., Titscher, P., Bognar, N., Schmuch, R., Winter, M., Kwade, A. and Herrmann, C. (2018) Exploring the Effect of Increased Energy Density on the Environmental Impacts of Traction Batteries: A Comparison of Energy Optimized Lithium-Ion and Lithium-Sulfur Batteries for Mobility Applications. *Energies*. 11 (1), pp. 150.

Chen, H., Cong, T.N., Yang, W., Tan, C., Li, Y. and Ding, Y. (2009) Progress in electrical energy storage system: A critical review. *Progress in Natural Science*. 19 (3), pp. 291–312.

Chen, Z., Kim, G.-T., Chao, D., Loeffler, N., Copley, M., Lin, J., Shen, Z. and Passerini, S. (2017) Toward greener lithium-ion batteries: Aqueous binder-based LiNi0.4Co0.2Mn0.4O2 cathode material with superior electrochemical performance. *Journal of Power Sources*. 372 pp. 180–187.

Davidson, A.J., Binks, S.P. and Gediga, J. (2016) Lead industry life cycle studies: environmental impact and life cycle assessment of lead battery and architectural sheet production. *The International Journal of Life Cycle Assessment*. 21 (11), pp. 1624–1636.

Deutz, P., Baxter, H., Gibbs, D., Mayes, W.M. and Gomes, H.I. (2017) Resource recovery and remediation of highly alkaline residues: A political-industrial ecology approach to building a circular economy. *Geoforum*. 85 pp. 336–344.

Dunn, J.B., Gaines, L., Kelly, J.C., James, C. and Gallagher, K.G. (2015) The significance of Li-ion batteries in electric vehicle life-cycle energy and emissions and recycling's role in its reduction. *Energy & Environmental Science*. 8 (1), pp. 158–168.

Dunn, J.B., Gaines, L., Sullivan, J. and Wang, M.Q. (2012) Impact of Recycling on Cradle-to-Gate Energy Consumption and Greenhouse Gas Emissions of Automotive Lithium-Ion Batteries. *Environmental Science & Technology*. 46 (22), pp. 12704–12710.

Ellingsen, L.A.-W., Hung, C.R. and Strømman, A.H. (2017) Identifying key assumptions and differences in life cycle assessment studies of lithium-ion traction batteries with focus on greenhouse gas emissions. *Transportation Research Part D: Transport and Environment.* 55 pp. 82–90.

Ellingsen, L.A.-W., Majeau-Bettez, G., Singh, B., Srivastava, A.K., Valøen, L.O. and Strømman, A.H. (2014) Life Cycle Assessment of a Lithium-Ion Battery Vehicle Pack. *Journal of Industrial Ecology.* 18 (1), pp. 113–124.

EUROBAT, ACEA, JAMA, KAMA and ILA (2014) *Resource Availability of Metals used in Batteries for Automotive Applications.* Available from: https://www.acea.be/publications/article/resource-availability-of-metals-used-in-batteries-for-automotive-application.

European Commission (2018) *COMMISSION STAFF WORKING DOCUMENT Report on Raw Materials for Battery Applications Brussels, 17.5.2018 SWD(2018) 245 final.* Available from: https://ec.europa.eu/transport/sites/transport/files/3rd-mobility-pack/swd20180245.pdf.

Gaines, L. (2014) The future of automotive lithium-ion battery recycling: Charting a sustainable course. *Sustainable Materials and Technologies*. 1–2 pp. 2–7.

Gallagher, K.G., Goebel, S., Greszler, T., Mathias, M., Oelerich, W., Eroglu, D. and Srinivasan, V. (2014) Quantifying the promise of lithium–air batteries for electric vehicles. *Energy & Environmental Science.* 7 (5), pp. 1555.

Ganter, M.J., Landi, B.J., Babbitt, C.W., Anctil, A. and Gaustad, G. (2014) Cathode refunctionalization as a lithium ion battery recycling alternative. *Journal of Power Sources.* 256 pp. 274–280.

Grey, C.P. and Tarascon, J.M. (2017) Sustainability and in situ monitoring in battery development. *Nature Materials*. 16 (1), pp. 45–56.

Heelan, J., Gratz, E., Zheng, Z., Wang, Q., Chen, M., Apelian, D. and Wang, Y. (2016) Current and Prospective Li-Ion Battery Recycling and Recovery Processes *JOM*. doi:10.1007/s11837-016-1994-y.

Heymans, C., Walker, S.B., Young, S.B. and Fowler, M. (2014) Economic analysis of second use electric vehicle batteries for residential energy storage and load-levelling. *Energy Policy*. 71 pp. 22–30.

Huskinson, B., Marshak, M.P., Suh, C., Er, S., Gerhardt, M.R., Galvin, C.J., Chen, X., Aspuru-Guzik, A., Gordon, R.G. and Aziz, M.J. (2014) *A metal-free organic–inorganic aqueous flow battery. Nature.* 505 (7482), pp. 195–198.

Jeong, S.S., Böckenfeld, N., Balducci, A., Winter, M. and Passerini, S. (2012) Natural cellulose as binder for lithium battery electrodes. *Journal of Power Sources*. 199 pp. 331–335.

Keskinen, M. and Valkama, J. (2009) End-of-Life challenges of printed electronics. In: *2009 IEEE International Symposium on Sustainable Systems and Technology*. May 2009 (no place) IEEE. pp. 1–5.

Kunnari, E., Valkama, J., Keskinen, M. and Mansikkamäki, P. (2009) Environmental evaluation of new technology: printed electronics case study. *Journal of Cleaner Production*. 17 (9), pp. 791–799.

Larcher, D. and Tarascon, J.-M. (2015) Towards greener and more sustainable batteries for electrical energy storage. *Nature Chemistry*. 7 (1), pp. 19–29.

Larsson, F., Andersson, P., Blomqvist, P. and Mellander, B.-E. (2017) Toxic fluoride gas emissions from lithium-ion battery fires. *Scientific Reports*. 7 (1), pp. 10018.

Lastoskie, C.M. and Dai, Q. (2015) Comparative life cycle assessment of laminated and vacuum vapor-deposited thin film solid-state batteries. *Journal of Cleaner Production*. 91 pp. 158–169. A

Lebedeva, N.P. and Boon-Brett, L. (2016) Considerations on the Chemical Toxicity of Contemporary Li-Ion Battery Electrolytes and Their Components. *Journal of The Electrochemical Society.* 163 (6), pp. A821–A830.

Leung, P., Shah, A.A., Sanz, L., Flox, C., Morante, J.R., Xu, Q., Mohamed, M.R., Ponce de León, C. and Walsh, F.C. (2017) Recent developments in organic redox flow batteries: A critical review. *Journal of Power Sources.* 360 pp. 243–283.

Mancini, M., Nobili, F., Tossici, R., Wohlfahrt-Mehrens, M. and Marassi, R. (2011) High performance, environmentally friendly and low cost anodes for lithium-ion battery based on TiO_2 anatase and water soluble binder carboxymethyl cellulose. *Journal of Power Sources*. 196 (22), pp. 9665–9671.

Mathieux, F., Ardente, F., Bobba, S., Nuss, P., Blengini, G., Alves Dias, P., Blagoeva, D., Torres De Matos, C Wittmer, D., Pavel, C., Hamor, T., Saveyn, H., Gawlik, B., Orveillon, G., Huygens, D., *et al.* (2017) *Critical raw materials and the circular economy Background report. JRC Science-for-policy report, EUR 28832 EN.*

Motavalli, J. (2015) Technology: A solid future. *Nature*. 526 (7575), pp. S96–S97.

Nguyen, T.H., Fraiwan, A. and Choi, S. (2014) Paper-based batteries: A review. *Biosensors and Bioelectronics*. 54 pp. 640–649.

Nordelöf, A., Messagie, M., Tillman, A.-M., Ljunggren Söderman, M. and Van Mierlo, J. (2014) Environmental impacts of hybrid, plug-in hybrid, and battery electric vehicles—what can we learn from life cycle assessment? *The International Journal of Life Cycle Assessment*. 19 (11), pp. 1866–1890.

Oliveira, J., Costa, C.M. and Lanceros-Méndez, S. (2018) Printed Batteries. In: *Printed Batteries*. Chichester, UK: John Wiley & Sons, Ltd. pp. 1–20.

Olivetti, E.A., Ceder, G., Gaustad, G.G. and Fu, X. (2017) Lithium-Ion Battery Supply Chain Considerations: Analysis of Potential Bottlenecks in Critical Metals. *Joule*. 1 (2), pp. 229–243.

Peters, J., Buchholz, D., Passerini, S. and Weil, M. (2016) Life cycle assessment of sodium-ion batteries. *Energy & Environmental Science*. 9 (5), pp. 1744–1751.

Peters, J.F., Baumann, M., Minke, C., Tomasini Montenegro, C. and Weil, M. (2018) The relevance of the end-of-life stage for the environmental impact of batteries. In: *SETAC*. 2018 Rome.

Peters, J.F., Baumann, M., Zimmermann, B., Braun, J. and Weil, M. (2017) The environmental impact of Li-Ion batteries and the role of key parameters – A review. *Renewable and Sustainable Energy Reviews*. 67 pp. 491–506.

Peters, J.F., Baumann, M.J. and Weil, M. (2018) Bewertung neuer Batterietechnologien für stationäre Energiespeicherung unter Umweltaspekten. In: *Battery Experts Forum*. 2018 Aschaffenburg.

Placke, T., Kloepsch, R., Dühnen, S. and Winter, M. (2017) Lithium ion, lithium metal, and alternative rechargeable battery technologies: the odyssey for high energy density. *Journal of Solid State Electrochemistry*. 21 (7), pp. 1939–1964.

Podias, A., Pfrang, A., Di Persio, F., Kriston, A., Bobba, S., Mathieux, F., Messagie, M. and Boon-Brett, L. (2018) Sustainability Assessment of Second

Use Applications of Automotive Batteries: Ageing of Li-Ion Battery Cells in Automotive and Grid-Scale Applications. *World Electric Vehicle Journal.* 9 (2), pp. 24.

Ramoni, M.O. and Zhang, H.-C. (2013) End-of-life (EOL) issues and options for electric vehicle batteries. *Clean Technologies and Environmental Policy*. 15 (6), pp. 881–891.

Reddy, T. (2011) Linden's Handbook of Batteries. McGraw-Hill: NewYork.

Richa, K., Babbitt, C.W. and Gaustad, G. (2017) Eco-Efficiency Analysis of a Lithium-Ion Battery Waste Hierarchy Inspired by Circular Economy. *Journal of Industrial Ecology*. 21 (3), pp. 715–730.

Savage, N. (2015) Electrochemistry: Liquid assets. *Nature.* 526 (7575), pp. S98–S99.

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

Sharifi, F., Ghobadian, S., Cavalcanti, F.R. and Hashemi, N. (2015) Paper-based devices for energy applications. *Renewable and Sustainable Energy Reviews*. 52 pp. 1453–1472.

The Royal Society (2017) *The Internet of Things: opportunities and threats.* Available from: https://royalsociety.org/science-events-and-lectures/2017/10/tof-internet-of-things/.

Tsurukawa, N., Prakash, S. and Manhart, A. (2011) Social impacts of artisanal cobalt mining in Katanga, Democratic Republic of Congo. *Öko-Institut eV – Institute for Applied Ecology, Freiburg.*

Vaalma, C., Buchholz, D., Weil, M. and Passerini, S. (2018) A cost and resource analysis of sodium-ion batteries. *Nature Reviews Materials.* 3 (4), pp. 18013.

Weber, A.Z., Mench, M.M., Meyers, J.P., Ross, P.N., Gostick, J.T. and Liu, Q. (2011) Redox flow batteries: a review. *Journal of Applied Electrochemistry.* 41 (10), pp. 1137–1164.

Weil, M., Ziemann, S. and Peters, J. (2018) The Issue of Metal Resources in Li-Ion Batteries for Electric Vehicles. In: Pistoia G., Liaw B. (eds) *Behaviour of Lithium-Ion Batteries in Electric Vehicles*. Springer, Cham. pp. 59–74.

Winslow, K.M., Laux, S.J. and Townsend, T.G. (2018) A review on the growing concern and potential management strategies of waste lithium-ion batteries. *Resources, Conservation and Recycling.* 129 pp. 263–277.

Xin, S., Yin, Y.-X., Guo, Y.-G. and Wan, L.-J. (2014) A High-Energy Room-Temperature Sodium-Sulfur Battery. *Advanced Materials*. 26 (8), pp. 1261–1265.

Zeng, X., Li, J. and Singh, N. (2014) Recycling of Spent Lithium-Ion Battery: A Critical Review. *Critical Reviews in Environmental Science and Technology.* 44 (10), pp. 1129–1165.

Zheng, F., Kotobuki, M., Song, S., Lai, M.O. and Lu, L. (2018) Review on solid electrolytes for all-solid-state lithium-ion batteries. *Journal of Power Sources*. 389 pp. 198–213.

Finding information about the EU

Online

Information about the European Union in all the official languages of the EU is available on the Europa website at: https://europa.eu/european-union/index_en

EU publications

You can download or order free and priced EU publications at: https://publications.europa.eu/en/publications. Multiple copies of free publications may be obtained by contacting Europe Direct or your local information centre (see https://europa.eu/european-union/contact_en).

Getting in touch with the EU

In person

All over the European Union there are hundreds of Europe Direct information centres. You can find the address of the centre nearest you at: https://europa.eu/european-union/contact_en

On the phone or by email

Europe Direct is a service that answers your questions about the European Union. You can contact this service:

- by freephone: 00 800 6 7 8 9 10 11 (certain operators may charge for these calls)
- at the following standard number: +32 22999696 or
- by email via: https://europa.eu/european-union/contact_en

KH-BB-18-006-EN-N

Keep up-to-date

Subscribe to Science for Environment Policy's fortnightly **News Alert** by emailing: **sfep@uwe.ac.uk**

Or sign up online at: http://ec.europa.eu/science-environment-policy

Publications Office