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Electrical energy storage for mitigating climate change

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Headlines

- Academic and industrial experts agree that effective electrical energy storage will play a crucial role in moving to a world powered by low-carbon electricity.
- Irrespective of the need to meet climate change targets, electrical energy storage technologies are essential to further enable the current rapid growth in renewable energy technologies, alongside other technologies to balance supply and demand.
- The electrical energy storage technologies that will be in use on a large scale within 5-15 years are likely to have already been invented, unless innovation and commercialisation radically speeds up over historical rates.
- Such technologies include: pumped hydropower, compressed air, thermal storage, electrolysis, aqueous batteries (e.g. lead-acid), non-aqueous batteries (e.g. lithium-ion, sodium-ion and lithium-sulphur), flow batteries (e.g vanadium redox flow, zinc bromide redox flow), power-to-gas, supercapacitors and flywheels.
- On many small islands and in remote communities, renewable electricity coupled with electrical energy storage is already the lowest cost option for electricity supply.
- Reliable clean electricity can be produced at a competitive cost through a grid powered by a high proportion of renewable energy coupled with electrical energy storage, and other technologies to balance supply and demand.
- Mechanical and thermal storage technologies, such as pumped hydropower, compressed air or thermal storage, require less energy to build, and use less toxic materials than is typical for electrochemical technologies such as batteries, but are so far only widely used at a grid-scale.
- Electrochemical energy storage technologies are likely to do the majority of balancing supply and demand 'off-grid', and can play an important role in balancing as part of a grid.
- The environmental impact of an electrical energy storage technology relates to the energy, and scarce and toxic materials used in producing it, recycling procedures and how long the device lasts. Academia, industry and regulators should give greater consideration to each of these environmental impacts in directing fundamental and applied research, product development and deployment.
- Accelerating the development and deployment of electrical energy storage technologies will require further fundamental and applied research and development, support to encourage deployment, removal of policy barriers and improvements to market structures.

Contents

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Introduction

Electrical energy storage devices are capable of storing electrical energy for use when supply fails to meet demand. These devices are likely to play an increased role in a future energy system, where a higher proportion of electrical energy is generated using intermittent renewable technologies, such as wind and solar. Electricity from these sources is generated intermittently and they cannot guarantee sufficient supply of electricity on demand by themselves.

There are a number of factors that make it challenging to plan how electrical energy storage can contribute to a reliable, clean future energy system. Firstly, electrical energy storage technologies have not been trialled on a sufficiently large scale. Secondly, there are a wide range of storage technologies, and for many of these the costs and technical characteristics are not yet well-defined. Finally, there is much uncertainty around the structure of the future energy system so it is challenging to make decisions around the role for electrical energy storage.

In this briefing paper, we explore the role that electrical energy storage technologies could play in supporting a cost-effective transition to an electricity system that emits a lower level of greenhouse gases – a so-called low-carbon electricity system. We then outline the specific technologies capable of filling this role. We consider the environmental impact of these technologies, potential routes for short- and longer-term technological developments, and the role of policy in supporting both their development and deployment. We have not considered other forms of flexibility, such as demand-side management, increased interconnectivity and heat storage in detail in this report but they could also play an important role in a rapid and cost-effective transition to a low-carbon electricity system.

An infographic comparing common technologies can be found on pages 12-13. These technologies are described in more detail in Appendix A (page 16) and a glossary of useful terms is provided on page 14.

What role could storage play in moving towards a low-carbon electricity system?

In the past, electricity has predominantly been produced by the combustion of fossil fuels with large 'base load' generators (e.g. coal plants) providing a constant level of supply, and other 'flexible' generators (e.g. gas plants or flexible hydropower) that provide additional electricity at times of peak demand. This electricity has then been distributed to consumers via a grid system. In 2014, electricity production accounted for around 15 per cent of global energy consumption, and this proportion is growing rapidly. In the same year, approximately 66 per cent of global electrical energy was produced from fossil fuels, and less than five per cent from solar and wind power[1]. Since emissions from fossil fuels contribute significantly to climate change, it is necessary to change the current system for producing energy in order to limit global warming to well below 2°C above pre-industrial levels, as stated in the 2015 Paris Agreement[2]. A number of strategies that could help to significantly reduce greenhouse gas emissions from the energy sector are laid out in the UK's 2011 Carbon Plan (summarised in Figure 1)[3]. The Intergovernmental Panel on Climate Change (IPCC) have established a similar set of global strategies in their 5th Assessment Report[4].

As shown in Figure 1, one possible pathway to lowering greenhouse gas emissions involves generating a higher proportion of electricity from renewables, coupled with changes in peoples' behaviour around energy use and falling costs for renewables and storage. Rapidly falling costs are already driving an increase in renewable electricity generation. For example, solar photovoltaic (PV) module prices fell from $2-4 per watt-peak in 2005 to less than $1 per watt-peak in 2014[5]. In the same period, global capacity increased from less than 5 gigawatts (GW) to more than 179 GW[5], with some analysts predicting more than 300 GW by the end of 2016[6]. Costs of onshore windpower have fallen more slowly, but remain one of the lowest cost sources of electrical energy, at around $0.06-0.09 per kilowatt hour. Cumulative installed onshore wind capacity increased from 193 GW in 2010 to more than 350 GW in 2014[5].

The International Energy Agency (IEA) states that, in order to limit global warming to below 2°C, rapid growth in these renewable energy sources must continue and that wind and solar PV could respectively generate 18 per cent and 16 per cent of global electricity by 2050. In a scenario where action on climate change only begins in 2030, the most economic strategy for meeting this target could involve deploying an additional 130 GW per year of solar PV capacity, and 75 GW per year of wind power over the period 2030-2040[7].

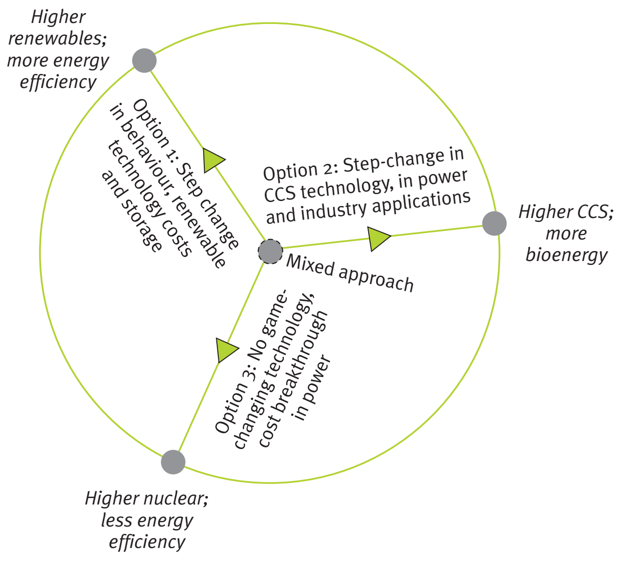


Figure 1: There are a range of approaches to lowering greenhouse gas emissions that are associated with changes to the energy system (adapted from UK Government 2011[3]). CCS = Carbon capture and storage technologies

Changes to the way electricity systems are operated will be required in order to accommodate an increasing proportion of intermittent renewable electricity from solar and wind power. This is because it is wasteful to curtail (disconnect) generators if their electricity is not immediately required[8], and although operating costs are low, there is a high capital cost to build renewables so it is wasteful to build a significant overcapacity. In addition, it is important to ensure that electricity is available to meet demand, as well as ensuring voltages and frequency of grid electricity meet required standards. Electrical energy storage could play an important role in meeting these challenges. The IEA estimates that in order to limit global warming to below 2°C, the capacity of storage connected to the grid should increase from 140 GW in 2014 to 450 GW globally in 2050.

What benefits does storage bring to electricity systems?

Electrical energy storage can have a range of benefits[9,10] including:

Grid support, which describes a number of services that maintain the quality of electricity in the grid, including:

- Frequency response: the second-by-second and minute-by-minute balancing of supply and demand in a given. This maintains electrical supply at the alternating current (AC) frequency required by network providers' contracts. Much of this need can be met by technologies able to respond within around a minute[9], but 'enhanced frequency response' requires responses within one second[10].
- Voltage support (also known as reactive power): the input or removal of power from the grid in order to maintain a constant voltage. This service responds to local needs, requiring distributed storage, and requires a very fast response time (milliseconds-seconds).
- Load following: a mechanism to ensure sufficient power is available to meet demand, and to respond to fluctuations in electrical supply and demand on timescales of 15 minutes up to a few hours.
- Reserve capacity: backup generating capacity to be used in case of rapid loss of power (e.g. an unplanned power plant outage). This further classified into 'spinning' reserve, able to provide power at less than 15 minutes notice, and 'non-spinning' reserve, which takes longer to start up.

Balancing intermittency, which refers to smoothing peaks and troughs in power supply that result from the varying output of renewable energy sources like wind and solar power[11]. These variations could affect voltage, frequency, and power output, and increase the need for all of the grid support services listed above.

Daily peak shifting, which balances daily cycles of supply and demand. For example, in the UK, electricity demand tends to peak in the morning and evening, with a dip in the afternoon and at night. By contrast, output from solar PV peaks in the daytime, and outputs from wind power and base load generation do not correlate strongly with any particular time of day[12]. As such, there is a useful role for technologies that store electricity at regular times of excess supply, to feed back into the grid at times of excess demand. [i] Also see Box 1.

Seasonal storage, which involves the storage of electricity during one season for use in another season. In a UK context, this could mean storing excess energy, generated using solar power in the summer, for use during the winter, when demand for heating and lighting is higher. This does not require a technology with fast response, but does require one that is able to store very large quantities of electricity at a low cost.

Off-grid services, which involve balancing intermittency and daily demand in a micro-grid or an off-grid setting. Technologies capable of meeting this application must be economical in small units, have a good balance between energy capacity and power output, and be able to respond quickly to changes in supply or demand.

Electricity storage for transport, which must be mobile and able to provide power for electric vehicles and other transportation. The exact requirements vary depending on the form of transportation, but generally technologies for this application must have a high power- and energy-capacity for their mass and volume. For applications such as aviation and shipping where the storage device must be used for long periods between charges, it is more important to store large quantities of energy.

Less generation and transmission infrastructure. Electricity storage could allow electricity demand to be met with a smaller generating capacity, and, if it is distributed, could reduce the need for expensive infrastructure to transmit electricity between regions[13].

It helps to make a strong business case for storage technologies if they can acquire revenue from different markets simultaneously. For example, in the UK, if a rooftop solar PV and lithium-ion battery system is used only to supply electrical energy to a single household, it takes approximately twenty years to pay back investment in the system. However, the payback time reduces to around five years if a similar system is placed on a community rooftop, has access to dynamic grid pricing that is indicative of the cost of producing a unit of electrical energy at a given time, and is able to provide frequency response and other grid support services[13].

i. This is related to 'arbitrage', whereby electrical energy is stored when the electricity price is low (i.e. times of high supply and/or low demand) and resold when the electricity price is high (i.e. times of low supply and/or high demand).

Box 1: The California duck curve

The so-called California 'duck curve' (Figure 2) represents daily changes in the load profile on the electricity system in California, which are a result of rapid deployment of solar photovoltaic panels since 2015[14]. The high output from solar panels around midday produces the duck's 'belly', whilst the falling output, combined with rapidly increasing demand, in the evening, produce the duck's 'neck'. This trend is leading to an oversupply of electricity in the middle of the day, whilst making it increasingly challenging to meet demand in the evenings. Electrical energy storage could help to alleviate this problem by storing electrical energy during the daytime, and releasing it to meet rapidly rising demand during the evening. The challenges associated with the 'duck curve' appear to be becoming manifest more quickly than was initially expected; On one day in 2016, the 'belly' of the duck already approached levels close to those predicted for 2020, although the evening demand in the 'neck' has not yet reached the predicted levels[15].

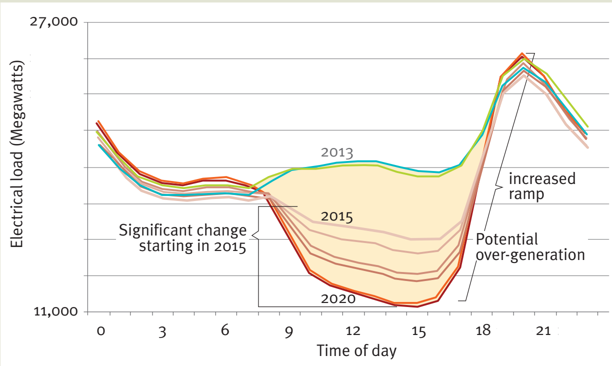


Figure 2: The California 'duck curve' shows how an electrical energy system can quickly become unbalanced without sufficient storage technologies.

What electrical energy storage technologies are available?

There are a large number of electrical energy storage technologies available with very different technical characteristics. Broadly, these may be grouped as follows:

- **Electrochemical storage technologies,** which store chemical potential energy (e.g. batteries).
- **Mechanical storage technologies,** which store mechanical potential energy (e.g. pumped hydroelectric storage, compressed air energy storage and flywheels).
- **Thermal storage technologies,** which store heat energy.
- **Electrical storage technologies,** which store energy in electrical fields (e.g. supercapacitors, supermagnetic energy storage).

In each case here, we refer to forms of electrical energy storage, but drop the words 'electrical energy' for conciseness.

Care should be taken to avoid confusion with other forms of storage in other contexts (particularly around thermal storage, where heat may be stored and used directly, rather than being converted back to electricity). Figure 8 summarises the roles that a few of the most promising technologies could play. Appendix A provides a more detailed description of these technologies, key variants within each technology category, deployment status, prospects and limitations, potential for future developments and environmental impact.

At this time, significant uncertainties remain around the costs, technical characteristics, environmental impact, and therefore potential role for different storage technologies, because:

- Cost ranges are wide since many technologies are immature, and cost estimates are often restricted by a lack of clear and authoritative data[16–18].
- Different variants of a technology may have very different costs and technical performance, which require a high degree of technical expertise to make use of.
- Details on how technologies may develop are sparse (again owing to technological immaturity)[18].

For the reasons outlined above, there has not yet been an authoritative and comprehensive comparison of storage technologies from which to make an informed decision on future changes to the structure of the electricity system. However, a number of reports present details about the different technologies[16–21]. We explore an example of the current and projected costs of lithium-ion batteries in Box 4 (page 19).

Broadly, electrical energy storage technologies may be grouped into those most suitable for (1) storing and delivering large quantities of electrical energy ('high energy', e.g. pumped hydropower, compressed air, flow batteries, hydrogen, liquid air and pumped heat), (2) storing and delivering electrical energy rapidly ('high power' e.g. capacitors, flywheels and superconducting magnetic energy storage) and (3) a combination of both (e.g. batteries). The future electricity system is likely to need a range of appropriate, safe and affordable storage solutions to fulfill both high power and high energy services at a range of spatial scales[22,23].

What are the alternatives to electrical energy storage?

Apart from electrical energy storage, there are a number of other methods ('flexibility measures', sometimes also referred to as classes of 'smart energy technology') for providing services to balance and maintain the reliability of electricity on the grid. In some instances these will complement, and in other cases compete with, electrical energy storage[18]. A few of these are summarised in this section:

- **Increased interconnectivity** is brought about by constructing additional transmission (between regions) and/or distribution (local) lines to transfer electrical power from one geographical location to another. An increased level of connectivity can help to smooth peaks and troughs in electrical supply and demand. This is true both at a micro-grid scale (where adding more households and renewable sources smooths the level of demand between peak times) and at a much larger scale (by exploiting the shift in daily peaks of supply and demand between regions), as well as variability in the level of wind and sunlight[24].
- **Demand side response** means adjusting electrical demand in anticipation of, or response to, changes in the available supply of electrical power from the grid. For example, at a household level this could involve running dishwashers or storage heaters at night when demand is low. At an industrial level it could mean shutting off parts of a factory at times of peak electrical demand[25,26]. Electrification of heating and transport could offer additional potential for demand side response.
- **Flexible generation** means generating power immediately as it is needed, using technologies such as gas turbines, hydroelectric and tidal power. These may be rapidly ramped up and down in order to react to changes in supply and demand[9].

Recent analysis suggests that each of these flexibility measures could play an important role in a future low-carbon electricity system. In order to meet electricity demand in a cost-effective way, whilst following the 'higher renewables, more energy efficiency' pathway for the UK energy system (Figure 1), researchers suggest connecting up to 3-12 GW of storage to the grid, building new interconnections totalling 13 GW of capacity between the UK and Ireland, and the UK and mainland Europe, and building 33-69 GW of flexible generators[27]. Demand side response would also be expected to play an important role.

Whilst not the focus of this paper, it is important to understand the role of storage not just in electricity systems but in whole energy systems. This could include generating and storing heat from electricity[28,29] and potentially converting electricity to hydrogen for transport[30].

Electricity storage need not always compete with other flexibility measures. For example, nearly self-sufficient micro-grids and buildings with integrated renewables and storage could play an important role in supporting grid power[31].

What improvements in electrical energy storage technologies are anticipated in the next 5-15 years?

Recent analysis of a range of energy and non-energy technologies reveals that the average time from invention to commercialisation is about 40 years[32]. Electricity generating technologies typically have some of the longest commercialisation times (average 48 years), but lithium-ion batteries for consumer electronics took just 19 years. This still implies that the electricity storage technologies that become widespread within the next 5-15 years will most likely have been through the research and development phase already, or perhaps will involve small changes to a technology under development or deployed now.

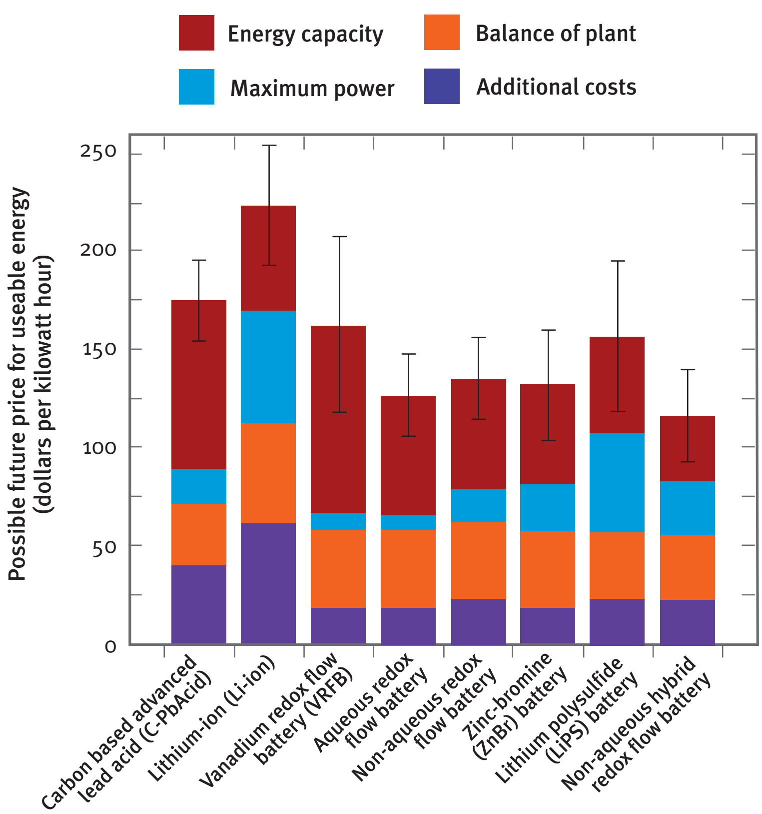


Figure 3: Projected future prices of a range of electrochemical energy storage technologies indicate that a range of technologies could be cost-effective in the future.

Prices are separated into materials costs associated with energy capacity and maximum power output, balance of plant, and additional costs, including depreciation, overhead, labour, etc.[35].

(Adapted with permission from reference 35)

The potential for, and likely areas of, innovation differ greatly between technologies (see Figure 8). Pumped hydropower, for example, is relatively mature compared with other large, grid-scale storage technologies. Future developments may allow this technology to operate at smaller scales and in geographies where they have not previously been used. Other technologies, such as compressed air energy storage and thermal electrical storage, have yet to be widely trialled at a grid scale (see case study in Box 2), but largely rely on established components. Here, future innovation may lead to new variants and components that are better optimised for specific applications, potentially reducing the devices' cost and increasing their efficiency and lifetimes.

Electrochemical technologies vary greatly in their maturity. For example, lead-acid batteries are mature for use as starters for internal combustion engines in vehicles, powering low-power vehicles such as milk floats in the UK, and have been widely deployed for stationary applications. Lithium-ion batteries are mature for use in portable electronic devices (such as mobile phones and laptops), but are less mature for larger scale applications (such as electric vehicles and stationary storage), and remain the subject of much research. These batteries have received an exceptionally high degree of attention from researchers and companies in recent years, largely driven by their utility in electric vehicles. In research, fundamental scientists are seeking new cell chemistries, and engineers are developing better techniques for manufacturing and managing battery packs. Improvements in these areas could lead to lower costs, longer battery lifetimes, and higher power- and energy- densities. However, any battery system is likely to involve some tradeoff between these parameters. Recent cost reductions for this technology are also likely to be the result of 'learning by doing' as the scale of their industrial production increases[33]. We go into more detail on the range of future cost and performance projections for this technology in Box 4. Many of the techniques discussed could be applied to other technologies, and in many cases the sources of innovation are likely to be similar.

Other electrochemical technologies such as redox flow batteries, high temperature sodium-sulphur batteries, electrolysis, and electrical technologies such as supercapacitors, and superconducting magnetic energy storage, have all been successfully deployed but have not yet reached the broader market. Until now, most attention has been paid to these devices in basic research. However some are being produced commercially on a small scale, and scaling up the production of these technologies could reduce costs and help to ensure they are available to fulfil their potential role in the future electricity system. Figure 3 shows projected prices for a range of developing battery technologies in a future scenario where one per cent of all energy generated is stored in the battery type in question. This figure indicates that many battery technologies could be affordable in the long term. There are a number of promising electrical energy storage technologies that could benefit from further research, including thermal storage, compressed air energy storage, and a number of electrical and electrochemical storage technologies[34].

Box 2: Grid-scale storage case study – liquid air energy storage pilot plant, Slough, UK

Picture reproduced with permission from Highview Power Storage

The firm Highview Power commissioned and operated a 350 kW/2.5 MWh liquid air energy storage (LAES) pilot plant between July 2011 and November 2014. It was co-located with a biomass heat and power plant in Slough, UK, in order to make use of waste heat to improve its operating efficiency[72]. The pilot plant was connected to the grid and subjected to a full testing regime, and has now been transported to be installed at the Centre for Cryogenic Energy Storage, University of Birmingham. With support from the UK Department for Energy and Climate Change (DECC), a pre-commercial five megawatt demonstration plant (pictured) has been constructed, co-located with a landfill gas generation plant near Manchester. When complete, this plant is expected to provide short term operating reserve (with hours of supply at hours of notice), support during winter peaks, and undergo testing for the US regulation market.

Is it possible to provide a reliable electricity supply at an acceptable cost using electrical energy storage coupled with intermittent renewables?

It is becoming increasingly possible for electrical energy storage coupled with intermittent renewables to provide a reliable electricity supply at an acceptable cost. This is in large part thanks to rapidly falling costs of key renewable electricity generation technologies, as well as storage technologies.

For example, in the UK and Germany, wind turbines based on land (known as 'onshore wind' power) are now the lowest cost method of generating electrical energy[37]. Furthermore, in some parts of almost all countries in central and southern Europe, the cost of electricity from unsubsidised solar PV is below the retail price of grid electricity[38]. Analysis shows the UK electricity system could cost over £5 billion less per year by 2030 if it produced only 50 grams of carbon dioxide per kilowatt

The energy trilemma

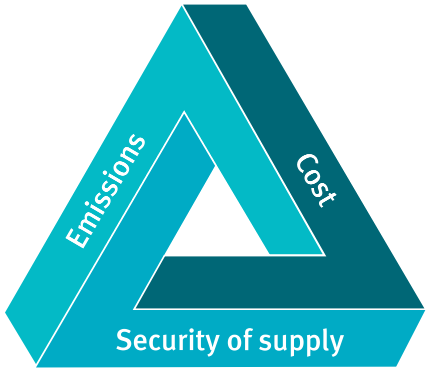


Figure 4: It is challenging to design an energy system that is simultaneously affordable, able to provide a reliable supply of energy, and does not result in unacceptably high emissions of greenhouse gases. This challenge is referred to as the 'energy trilemma'.

hour was powered by more intermittent renewables (supplying approximately two-thirds of electricity) and made greater use of the flexible technologies – compared with a system that has low flexibility and no renewables (see Figure 5)[36]. These savings chiefly arise through reduced capital investment in nuclear power, and reduced capital investment in, and operating costs of, carbon capture and storage – which more than compensate for increased capital investment in renewable energy sources. The same analysis indicates that flexibility measures in the electricity system could lead to savings of £2-3 billion per year even if emissions only drop to 200 grams of carbon dioxide per kilowatt hour. Electricity costs for UK consumers would not need to be significantly higher than a system dominated by fossil fuels, even with renewables contributing up to 80 per cent of electricity supply[39].

Data from the eastern United States shows that electricity can be produced at 9-15 cents per kilowatt hour, with wind and solar PV contributing 90 per cent of electrical energy, and incorporating three electrical energy storage technologies (centralised hydrogen, centralised batteries and grid-integrated battery electric vehicles). This is comparable to electricity from the predominant fossil fuel-based system, which costs 8 cents per kilowatt hour, and reliably meets the same demand[40]. With sufficient advances in technology, electricity provided by solar PV (backed up with appropriate storage) could match the cost of coal power in most world regions by 2025[41].

In many countries, small communities may share an isolated electricity system referred to as a 'micro-grid', often chiefly powered by renewables and electricity storage. Many of these already supply electricity at a favourable price[42], and offer many co-benefits for quality of life, education and healthcare with minimal greenhouse gas emissions (see Box 3). For example, solar PV with electricity storage is the most economically viable means for electricity supply in large regions of Africa (see Figure 6)[43]. Whilst in rural India, analysis suggests that the cost of electricity from a domestic off-grid system with solar PV and storage supplying more than 90 per cent of demand will meet the cost of off-grid diesel generation by around 2018.

Box 3: Micro-grid case study – Isle of Eigg, Scottish Inner Hebrides, UK

Components of the Eigg electricity system from top left: Solar PV arrays, wind turbines, battery bank, diesel generator, inverters system, hydropower turbine. Picture reproduced with permission from reference 96

Eigg is a small island in the Scottish Inner Hebrides with a population of less than a hundred. Eigg is not connected to the mainland electricity grid, but meets the energy needs of islanders using a small independent grid powered by an array of solar panels, four small wind turbines, a hydro turbine, a bank of lead-acid batteries and a diesel generator[97]. About 90 per cent of electricity used in Eigg comes from renewable sources. Island residents each have a capped load of five kilowatts, and there is a penalty if this load is exceeded, although this has rarely been needed. The cost of the energy system fell below quotes for mainland connection, with funding provided from a range of regional and European sources and by the islanders themselves, and government subsidy schemes for renewables represent an important revenue stream[96]. This project demonstrates that micro-grid systems can be designed such as to be capable of supporting the electricity needs of a community leading modern lifestyles.

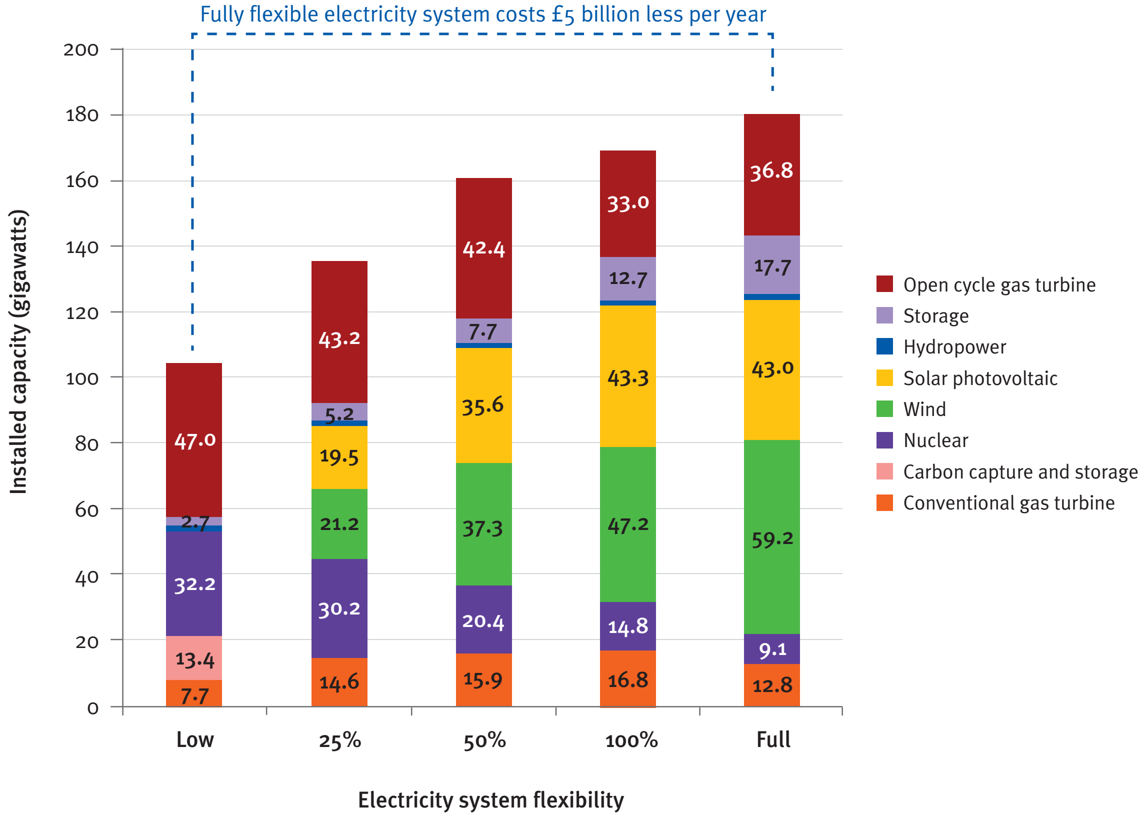


Figure 5: Mix of electricity generation technologies required to achieve 50 grams per kilowatt hour carbon intensity in 2030 with different levels of electrical energy system flexibility[36]

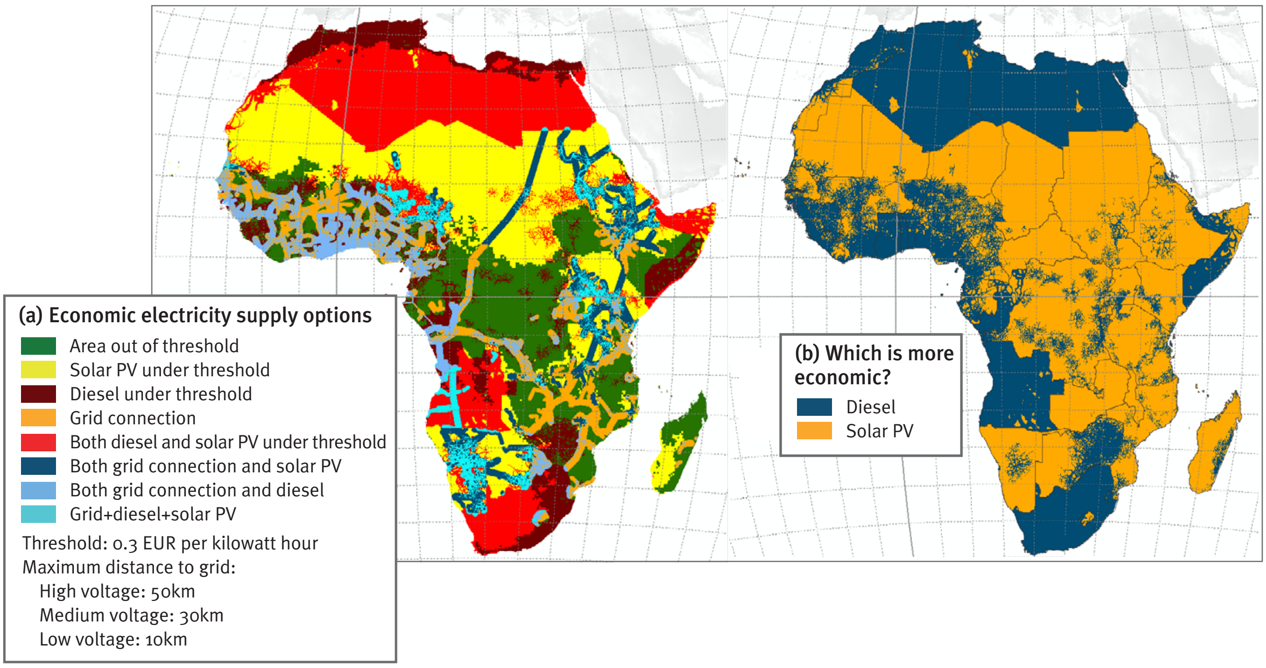


Figure 6: (a) Geographical distribution of technologies with electricity costs lower than 30 cents per kilowatt hour in 2011[ii], and a conservative assumption of the extension of the electricity grid, (b) Off-grid options in Africa: economic comparison of diesel versus solar photovoltaic. (from reference 43)

ii. Costs of both solar PV and electrical energy storage technologies have decreased significantly since these data were collected, and it is likely that a similar chart produced today would show this as the most viable option in a greater geographic area.

How do the environmental impacts of electrical energy storage technologies compare with their alternatives?

In assessing the effect technologies have on the environment, we consider the energy required to build them (the 'embedded energy'), any toxic components used, and how they can be recycled. Appendix A shows the potential environmental impact of several electrical energy storage technologies, although this is based on the limited number of scientific studies that have been conducted, which often rely on broad assumptions, or data that are limited or decades out of date[45–48]. As such, improving and updating the environmental assessments is a critical research priority .

One metric to measure the potential environmental impact of different bulk storage technologies is the energy stored on investment (ESOI)[iii], where a higher number indicates a better capacity to store energy, a long operating life time (cycle life), or a small amount of embedded energy[45].

$$\text{ESOI} = \frac{\text{the amount of energy stored over the lifetime of a device}}{\text{embedded energy}}$$

Mechanical energy storage technologies, such as pumped hydropower and compressed air energy storage, have a much higher ESOI than electrochemical energy storage technologies, such as batteries, by a factor of 10-100 (see Figure 7)[45]. This difference is a result of the mechanical technologies' lower embedded energy per unit capacity, and higher cycle life. Among batteries, cycle life varies greatly and this has the a significant effect on their ESOI. It follows that driving innovation to improve cycle life could be a good route towards reducing environmental impact. Further to this, the ESOI of a technology can be improved by extending its useful life, for example giving spent electric vehicle batteries a 'second life' in stationary applications such as grid or domestic storage[49,50].

A recent study in India showed that solar PV and storage systems can have significantly lower greenhouse gas emissions than diesel generators, even when accounting for their embedded energy. Here, an off-grid system produces 373-540 grams of carbon dioxide per kilowatt hour used over its lifetime, using a majority of electricity from silicon-based solar PV combined with lithium-ion battery storage, and a backup diesel generator to meet around 3-15 per cent of electrical energy demand. This is significantly lower than emissions from a system reliant solely on diesel generation, which produces 1056 grams of carbon dioxide per kilowatt hour used[44]. The solar panel currently contributes around three-quarters of the total emissions of this system, compared to less than five per cent from the lithium-ion battery. The greenhouse gas emissions of the system could be further reduced by more than 50 per cent by using non-silicon solar panels (such as cadmium telluride or, in the future, organic PV), which require less energy to produce. However, the emissions would be significantly increased by replacing the lithium-ion batteries with cheaper lead-acid batteries, which have a lower cycle life.

Additional environmental considerations for electrochemical technologies are the scarcity[51,52] and toxicity of materials used in their production[53,54]. Effective recycling procedures exist for lead-acid batteries in Europe and the US, where more than 95 per cent of lead-acid batteries are recycled at the end of their lives. This success has been attributed to the profitability of reclaimed recycled materials, the illegality of disposing of batteries, the simplicity of disassembling the standard design of batteries and the ease of recycling the components. However, a high incidence of lead poisoning in regions of developing world has been attributed to widespread informal recycling without proper safety equipment[55–57]. The World Health Organisation (WHO) estimates that each year lead poisoning contributes to 600,000 new cases of children developing intellectual developmental disorders, and accounts for 143,000 deaths[58], partly attributed to informal lead-acid battery recycling.

Lithium-ion batteries could also be hazardous without proper recycling at the end of their useful lives[53,59]. Recycling procedures are not well established and are more challenging than for lead-acid batteries, owing to a more complex design and a wider range of materials used in their construction[50]. Whilst there are a number of proposed solutions, an insufficient number of lithium-ion batteries have reached the end of their lives for recycling to become commercially viable. In addition, lithium-ion battery technology is still evolving, so recycling procedures developed for a specific design or chemistry could quickly become obsolete. Broad commitment from industry and government will be required to meet the challenge of developing effective recycling procedures before large numbers of electric vehicle lithium-ion batteries reach the end of their useful lives[50].

The rare earth metal cobalt is currently used in most lithium-ion batteries[33]. The Democratic Republic of the Congo is the source of 50 per cent of global cobalt, 40 per cent of which is used in battery production. However, its extraction from here has been associated with serious and systematic human rights violations and environmental negligence[60]. For this reason, some lithium-ion battery manufacturers are seeking to use cobalt from other sources[61], and make more use of lithium-ion cell types that do not use cobalt, such as iron phosphate cathodes[33,iv]. Similar challenges could arise in other electrochemical storage technologies, and careful attention should be paid to recyclability and resource use.

iii. It should be noted that the ESOI metric is only suitable for assessing bulk storage technologies, and may fail to capture the value of technologies that do not store large quantities of energy, but are capable of supplying smaller quantities of energy very rapidly for high power services (such as flywheels or supercapacitors). It may also fail to capture the ability of technologies to operate at small scales probably only viable for electrochemical technologies.

iv. These cell types tend to have a lower energy and power density, making them less suitable for smaller electric vehicles[16].

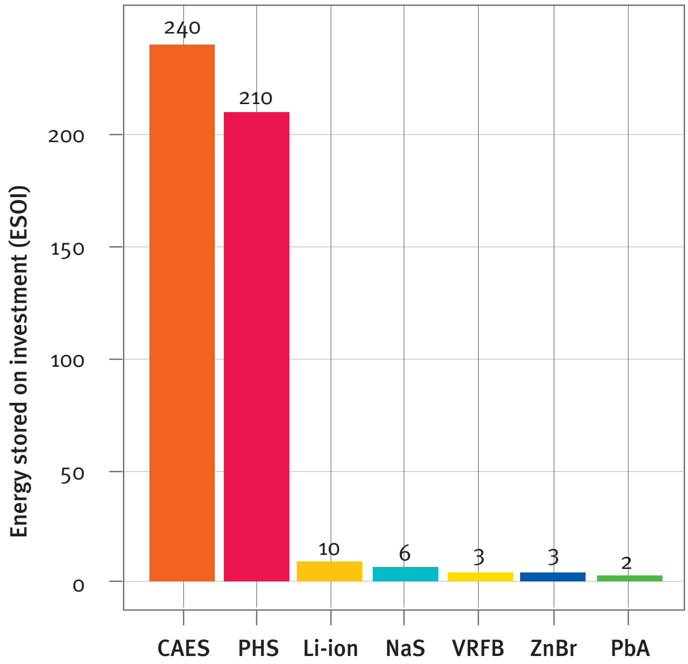


Figure 7: Environmental impact as measured by Energy Stored on Investment (ESOI) for a range of storage technologies. Mechanical energy storage technologies have a much higher value than electrochemical energy storage as a result of their lower embedded energy per unit capacity and higher cycle life[v].

(Reproduced with permission from reference 45)

- CAES = Compressed air energy storage
- PHS = Pumped hydropower storage
- Li-ion = Lithium-ion battery
- NaS = High temperature sodium-sulphur battery
- VRFB = Vanadium redox flow battery
- ZnBr = Zinc-bromide hybrid flow battery
- PbA = Lead-acid battery

When considering the environmental impacts of storage technologies, they should be compared with the environmental impacts of other low-carbon energy system options. All of the energy system pathways proposed by the UK Department for Energy and Climate Change (DECC) (see Figure 1) are likely to lead to significant increases in land and/or water use, except the 'higher renewables, more energy efficiency' pathway, according to a recent study[62]. Worldwide, coal combustion is estimated to contribute to 8.2-130 deaths and 74.6-1193 cases of serious illness per terawatt hour, chiefly associated with air pollution, compared to 0.074 deaths and 0.22 cases of serious illness per terawatt hour associated with nuclear power. The health impact of renewable electricity sources have been less comprehensively assessed, but academics expect the impact of solar, wind, and tidal power to be less severe than either coal or nuclear power[63]. Whilst carbon capture and storage technologies have the potential to reduce the emission of some air pollutants from fossil fuel combustion, they reduce the overall efficiency of electricity production and remain immature so their total effect is yet to be determined[64].

How can policies support innovation in, and deployment of, electrical energy storage technologies?

In this section, we summarise a number of ways that policy intervention could support the innovation in and deployment of energy storage technologies:

Removing regulatory barriers: A number of regulatory barriers currently hamper private and public sector efforts to deploy electrical energy storage technologies in the UK and other countries in Europe[65,66]. For example, connecting storage infrastructure to the grid in some countries in Europe incurs regulatory fees associated with generation and demand services, since they don't fall neatly into either category. This could be alleviated by creating new regulations specific to energy storage[65,67].

Clarifying the end-user: In addition, since electricity is considered to be consumed when it is stored, and again when it is delivered, electrical energy passing through a storage device is inappropriately charged consumption levies twice at present[67].

Policies to improve access to multiple sources of income: Many electrical energy storage technologies are technically able to fulfil a range of electricity system needs simultaneously (such as peak shifting, frequency response, and avoiding the need for additional generators). While it helps to make a strong business case for storage and other flexible technologies if they can acquire value from different markets simultaneously, some national contracts require technologies to be available solely to provide one service. Likewise, some domestic and small-scale

v. ESOI estimated at three for VRFBs, but higher life time estimates raise ESOI to above ten.

operators are unable to provide and receive income from some services that they have the technical potential to provide[13,67].

Market structures to improve access to multiple sources of income: At present, the price paid for electricity by many domestic users and small businesses is a flat rate, and does not vary with what that unit of electricity cost to generate (typically higher at times of peak demand). Developing market structures that offer providers better access the value of electricity generation at a given time would increase to the possible revenue offered by electricity storage technologies via, for example, energy arbitrage. This would also help to incentivise their deployment[13,68,69]. In the UK, planned moves towards smart metering and recording electricity use every half-hour for all users could help to facilitate this.

Technology support: Continuing public sector support has an important role to play in mitigating the risk of wasted capital for an investor (for example, by demonstrating lifetime and cost) so that the private or public sector can invest at a sufficient scale to meet growth in intermittent generation over the coming decades. This could include demonstrating and scaling-up technologies and ensuring their performance is improved through deployment and learning[65]. For longer-term technologies, basic research and development, and demonstration support are needed to overcome specific identified technical barriers to improving their performance and cost[13,34]. Details of possible innovations for particular technologies are provided in Appendix A.

Encouraging micro-grids and community projects: Micro-grids are likely to be an important application for renewables coupled with electrical energy storage, particularly in developing countries and remote areas. Raising capital for such projects can be a barrier but innovative means of financing, such as government- or community- financing, could have a positive effect, as could decreasing subsidies for fossil fuels. Cooperation between government, communities, businesses, utilities companies, and the private sector is vital to the success and sustainability of such projects[42].

Importance of contract length: The length of contracts is an important factor in how providers perceive the security of the electrical storage market. It also has implications for the technologies they chose, and investment in their development[70]. Contracts lasting just a few years allow providers the valuable option to replace the technology at the end of the contract period, and have often been chosen for this reason. However, some technologies have proven or projected lifetimes numbering tens of years, so contracts over these timescales could provide an incentive for investors to use and gain the value these technologies offer. Short contract lengths are also likely to promote cost-saving developments over increasing the lifetime of the technologies, which is potentially detrimental to the environment as devices are replaced more frequently.

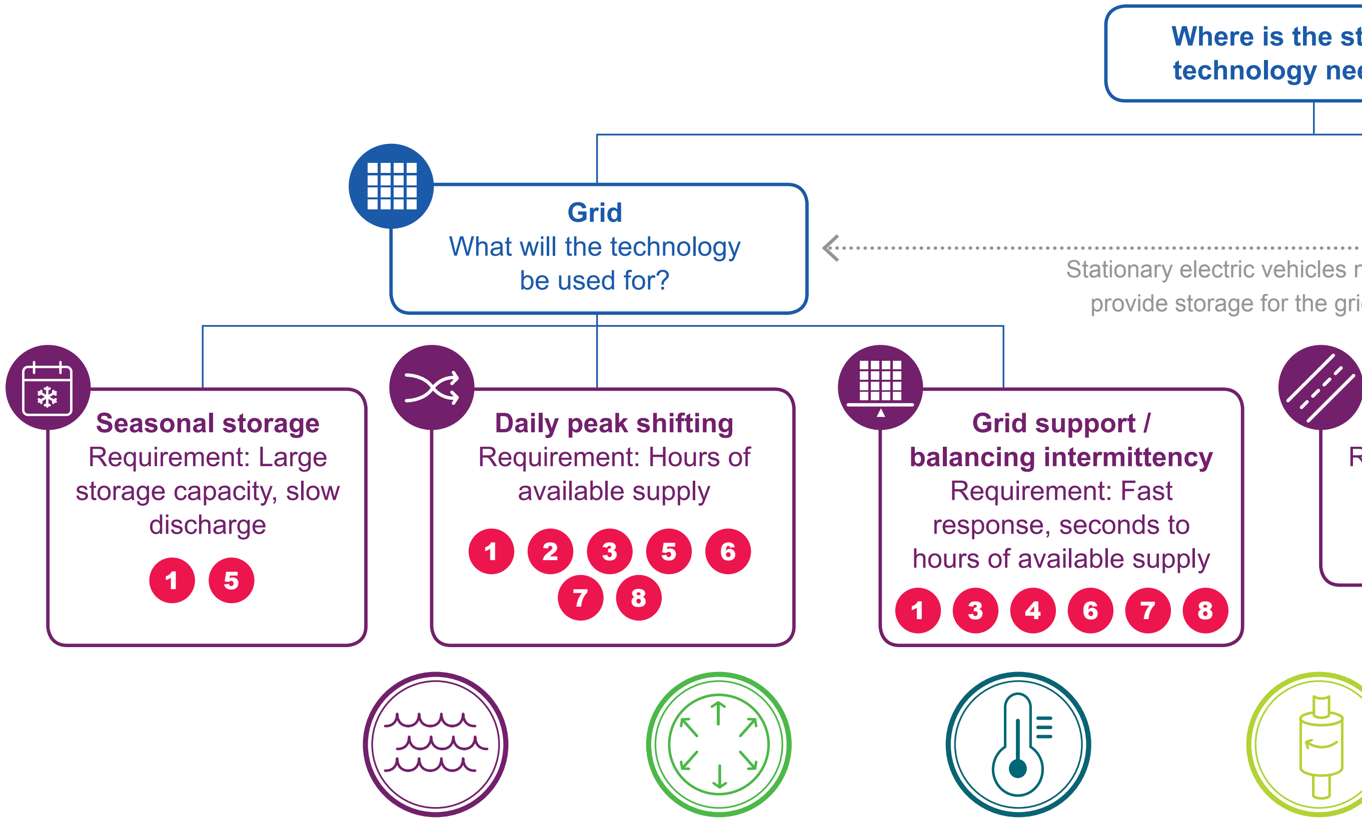
Regulation around environmental impact: Whilst some regulation exists around battery disposal, further policies and regulations could help to reduce the environmental impact of electrical energy storage technologies. These could include encouraging a greater focus on recyclability, embedded energy and device lifetime, and sourcing of resources at research and industry levels[45,50].

Summary

Electrical energy storage will have a number of benefits as the electricity system becomes increasingly reliant on intermittent renewables. A range of storage technologies exist, that have different performance characteristics and costs, ranging from low-cost, large-scale mechanical technologies to higher-cost electrochemical technologies. In many cases even the higher-cost technologies represent good propositions for a low-carbon electricity system, provided that their value can be realised across their multiple capabilities. In sunnier locations, off-grid systems of solar PV coupled with storage are already an economic proposition compared to much more polluting diesel generation.

A focus on innovative research and market support could reduce storage costs. This would bring about significant benefits in reducing the cost of very low-carbon systems with use of intermittent renewables rivaling traditional systems dominated by fossil fuels. In addition, adverse environmental and social impacts can be minimised by ensuring recyclability, longer technology lifetimes and appropriate sourcing of raw materials for a range of storage technologies. Policymakers now have a critical role in designing market policies to reap the value from storage, in supporting innovation, and in ensuring environmental impacts are minimised.

Figure 8: Which energy storage technology can meet my needs?



	1 Pumped hydropower	2 Compressed air energy storage	3 Thermal cycle	4 Flywheel supercap tors / SM
Capital cost	\$ – \$\$	\$ – \$\$	\$ – \$\$	\$\$ – \$\$\$
Cost per cycle	–	–	–	–
Response time	Seconds – Minutes	Minutes	Seconds	Milliseconds – M
Total deployment	3	2	1	1 / 2 /
Efficiency (%)	70 – 85	50 – 75	55 – 80	85 –
Daily self-discharge	<0.5%	<10%	0.5 – 1%	(100% / 5 – 20% / 1
In a nutshell	Affordable, but large and site-specific	Affordable, but large and site-specific	Potentially affordable, non site-specific	Fast response, bu discharge

Capital cost: (\$/kWh for 1 – 8hr energy system): \$ = 10 – 100, \$\$ = 100 – 1000, \$\$\$ = 1000 – 10,000)

Cost per cycle: (including capital/cycle life, and operation, and maintenance. units \$/kWh/cycle):

= < 0.01, = 0.01 – 0.10, = 0.10 – 1, = 1 – 10

Response time: Time a storage system requires to ramp up supply

Total deployment:

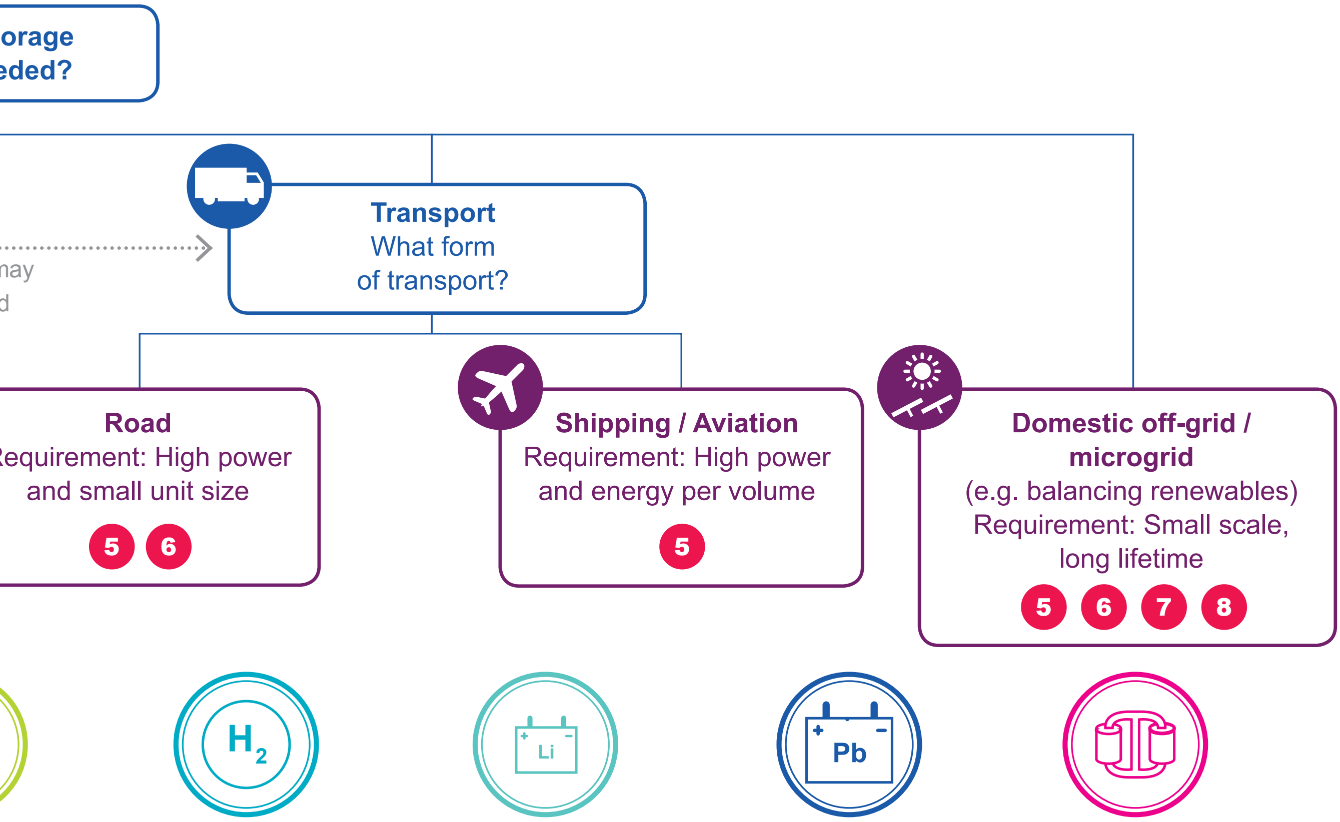
1 = less than 100 MW / 100MWh deplo

2 = 100 MW / 100 MWh to 10 GW / 10

3 = more than 10 GW / 10 GWh deploy

Efficiency: Energy out divided by energ

Daily self-discharge: Percentage of cha



s / paci- ES†	5 Hydrogen electrolyser / fuel cell	6 Lithium-ion batteries	7 Lead-acid batteries	8 Redox flow batteries
	$$$	$$	$ – $$	$$
	–	–	–	
Minutes	Minutes	Milliseconds	Milliseconds	Milliseconds
1	3	2	3	1
– 98	<40 (mature) Up to 66 (developing)	80 – 90	65 – 85	65 – 85
10 – 15%)	~0%	~0%	~0.2%	~0%
ut rapid	Potential for long-term storage, currently expensive	High energy density, rapidly developing	Mature, but bulky and toxic materials	High number of cycles in lifetime, but bulky

oyed
GWh deployed
ed
y in
rge lost in device each day

* Other measures, such as increased interconnectivity, demand side management, thermal storage and dispatchable generation, also play a part in regulating the supply of electricity

† Superconducting Magnetic Energy Storage

Glossary

Alternating current (AC)	An electric current that reverses its direction many times a second at regular intervals. Typically, electrical energy from rotating devices is supplied in this form.
Arbitrage	The storage of electrical energy when the electricity price is low (i.e. times of high supply and/or low demand) to be resold when the electricity price is high (i.e. times of low supply and/or high demand).
Balance of plant (BoP)	Supporting facilities and components in a storage system.
Balancing	Services designed to match supply and demand.
Base load	Electrical energy delivered or consumed at a constant rate.
Capacity (watts or W)	The maximum amount of power generated by a fleet of electrical energy generation devices when operating under normal conditions.
CAES	Compressed air energy storage.
Capital cost ($/kW, $/kWh)	Fixed, one-time expenses to build something, e.g. a storage device.
Carbon footprint (g CO_2 or g CO_2/kWh)	The amount of carbon dioxide emitted in building or operating a storage device or electricity system, often specified for each unit of energy delivered for a system, or storage capacity for a storage device.
Cell	Single, smallest energy- or charge-storing unit in a battery system.
Connectivity	The degree of electrical connection between generators and consumers in the electricity system (also 'Interconnectivity').
Cost per cycle ($/kWh/cycle)	Cost per provided unit of electrical energy, over a specified number of cycles.
Cycle	One cycle represents a single charge and discharge of an energy storage device, sometimes to a specified depth of discharge (also see "Depth of discharge" below).
Cycle efficiency (%)	The proportion of energy injected into a storage device upon charging that is recovered upon discharging.
Cycle life (# cycles)	The number of complete charge-discharge cycles before a device reaches the end of its useful life (may depend on other factors such as temperature, and rate and depth of charge and discharge).
Demand side management	Measures designed to influence the level or timing of customer demands for energy.
Demand side response (DSR)	Proactive changes in power consumption by utility customer to accommodate variability in supply.
Depth of discharge	The proportion of the maximum energy capacity of a device that is supplied when discharging that device.
Direct current (DC)	An electric current flowing in one direction only. Typically, electrical energy from non-rotating devices is supplied in this form.
Embedded energy (kWh or kWh/kWh)	The amount of energy required to produce a storage device, often specified for each unit of storage capacity.
Energy (kWh)	A physical property that can be transferred between objects and between forms. In this context, energy may be thought of as the capacity to do work.
Energy density – gravimetric (kWh/kg)	The maximum energy a storage system can deliver, divided by its mass.
Energy density – volumetric (kWh/m^3)	The maximum energy a storage system can deliver, divided by its volume.
Energy stored on investment (ESOI)	The amount of energy stored in a storage device over its lifetime divided by the energy required to produce that device.
Flexibility options	Services to balance and maintain the quality of electricity on the grid.
Flexible generation	Electrical energy generation technologies that are able to rapidly increase or reduce their output.
Frequency response (FR)	The ability of a system (or elements of a system) to respond to correct a change in the frequency of the alternating current of electricity on the grid.
Interconnectivity	See 'Connectivity'.
Intermittency	Uncontrollable variation in power supply or demand.
LAES	Liquid air energy storage.

Levelised cost of energy (LCOE)	Cost per unit of electric energy provided over a specified period number of years (often the useful lifetime of a device).
Li-Ion	Lithium-ion battery.
NaS	Sodium-sulphur battery.
Pack	A battery system consisting of a number of connected battery cells, together with power electronics, a battery management system, housing, and temperature control.
PbA, LA	Lead-acid battery.
Peak shifting	Shifting electrical power consumption from periods of maximum demand to other times.
Penetration	The proportion of a specific technology (or specific technologies) relative to all technologies that form a system.
PHES	Pumped heat energy storage.
PHS	Pumped hydropower storage.
Power (W)	The rate at which energy is delivered.
Power density – gravimetric (kW/kg)	The maximum power a storage system can provide, divided by its mass.
Power density – volumetric (kW/m^3)	The maximum power a storage system can provide, divided by its volume.
Quality of electricity	The reliability of electrical supply in terms of power, voltage, and consistency of frequency of alternating current.
Quality of supply	See 'Quality of electricity'.
Ramp rate (MW/minute)	The rate at which power output of a storage device can be increased or decreased.
Response time (seconds)	The length of time between the point when a device delivers no power, and the point when it delivers its maximum power.
Round trip efficiency (%)	See 'Cycle efficiency'.
Seasonal storage	The ability to store energy for days/weeks/months to compensate for seasonal supply and demand variability, or a long term supply disruption.
Self-discharge rate (%/day)	Unintended discharge of stored energy that occurs while a storage system is idle.
SMES	Superconducting magnetic energy storage.
Stationary storage	Energy storage systems providing services from a fixed geographical location (as opposed to mobile storage used in transport).
Useable energy capacity (kWh)	The maximum actual amount of energy that can be stored by a device, relative to its nominal energy capacity.
VRFB	Vanadium redox flow battery.
Watt peak (Wp)	The maximum power provided by an electrical energy generation device under normal conditions (e.g. a solar panel in full sun).
ZnBr	Zinc bromine battery.

Appendix A: Overview of energy storage technologies

Technology	Technical description	Key variants	Deployment status	Why is it promising?	What are its limitations?	Possible future developments	Environmental impact[vi]
Pumped hydropower storage (PHS)	Water pumped uphill during charge, released through turbine to discharge.	Operation always similar, but varies with specific site geography.	Mature, more than 100 GW deployed[71] (99% of world bulk storage capacity).	Proven technology for bulk storage, low cost over lifetime, relatively low carbon footprint[vii].	Site specific, long construction time, large unit size, and high capital costs[16].	Use in atypical geographies (e.g. small sites, coast) Cost reductions unlikely.	No major impact if carefully sited. ESOI = 210.
Compressed air energy storage (CAES)	Air compressed in underground cavern during charge, released through turbine to discharge.	Heat may be stored during compression and reused during expansion to increase cycle efficiency.	Total deployed capacity 400 MW in two demonstration plants, one has operated for more than 35 years.	Relies on mature components, could offer a robust and affordable bulk storage[vii].	Site specific[2], lower efficiency than PHS, some components require redesign to handle high pressures and extreme temperatures.	More efficient larger systems, and more cost-effective small systems.	Combustion of natural gas required if heat not stored efficiently. No other major impacts. ESOI = 240.
Thermal Cycle	Encompasses a number of technologies that store heat energy within insulated repositories, but involve different modes of operation.	Liquid air energy storage (LAES) liquefies air during charge, turning back to gas to drive a turbine to discharge. Pumped heat energy storage (PHES) pumps heat from a cold to a hot tank during charge, which is reversed to drive a turbine to discharge.	LAES: 350 kW/2.5 MWh pilot ran from 2011 – 2014 (See Box 4). 5 MW/15 MWh plant under construction[72]. PHES: Prototype stage[73].	Relies on mature components, could offer a robust and affordable bulk storage with no specific site requirements (although operates at higher efficiencies when co-located with industrial waste heat)[16].	More costly than other bulk storage options (such as pumped hydropower and compressed air). Unlikely to be suitable for very fast response.	Learning through scaling up, specific redesign of components for extreme temperatures and pressures. Could benefit from developments in heat storage for other applications.	Little formal assessment. Rely chiefly on mature and robust mechanical components, likely to have a relatively small environmental impact.
Flywheels	A low-friction wheel is accelerated during charge, and decelerated to power a generator to discharge.	Speed of rotation of wheel varies, governing length of time over which supply is possible.	Mature. ~1 GW deployed, primarily to power fusion reactors[80].	Rapid response, high power density, very high cycle life, high efficiency, and low maintenance.	Only able to supply power for short durations (<1hr), relatively high capital costs.	Material improvements leading to higher rotation speed, and longer supply duration.	Little formal assessment, reported to have a low carbon footprint[74].

Appendix A: Overview of energy storage technologies (continued)

Technology	Technical Description	Key Variants	Deployment Status	Why is it promising?	What are its limitations?	Possible Future Developments	Environmental Impact
Supercapacitors	An electrochemical device where thin metal strips separated by a thin dielectric layer are charged and discharged.	A range of dielectric materials may be used, however the impact on device performance largely remains to be assessed.	~30 MW deployed, primarily to provide network frequency regulation services[87].	Rapid response, high power density, very high cycle life, high efficiency, and low maintenance.	Only able to supply power for short durations (< 1hr), high cost.	Cost reduction and energy density improvements possible.	Little formal assessment. Some electrolyte materials might be toxic[75].
Superconducting magnetic energy storage (SMES)	Stores magnetic energy in a highly cooled superconducting metal coil[14,76,77].	Different materials operate at different temperatures and different costs.	More than 100 MW deployed, primarily to power fusion reactors[87].	Rapid response, high power density, very high cycle life, high efficiency[16,76,77].	Only able to supply power for short durations (< 1hr), high cost and complex architecture[16,78].	R&D focus on cost reduction, and more robust high temperature devices.	Little formal assessment. Cooling associated with energy cost. Strong magnetic fields may impact their environment[16].
Hydrogen electrolyser/fuel cell	Water is electrolysed to form hydrogen during charge. Hydrogen may be converted back to electricity using a fuel cell, or used directly in transport or industry.	Two commercial forms electrolyser exist. 'Alkaline' is more mature and lower cost, 'Proton exchange membrane' (PEM) is more flexible and responds more rapidly.	Alkaline: relatively mature (7.5-12 GW deployed). PEM: Developing (<20 MW pilot plants deployed).	Possible low-cost storage of gas makes promising for seasonal storage. Hydrogen is also a useful product for other sectors.	High cost, relatively low efficiency, slow response.	Cost reduction through technical improvements and scaling up of production. New forms of electrolyser are under development.	Relatively low carbon footprint, little assessment of toxicity of materials[79].
Lithium-ion battery	An electrochemical device where lithium ions shuttle between electrodes in battery cells during charge and discharge. Cells are combined with electronics to form a battery pack.	Various cell chemistries and pack designs. Batteries necessarily involve a trade-off between cost, cycle life, energy and power density.	Mature for consumer electronics. Deployed in vehicles, and grid and off-grid stationary applications[32]. Approximately 1GW/1GWh grid connected[80].	Capable of operating on- and off-grid, relatively high efficiency and cycle life, fast response. Costs and performance are rapidly developing (See Box 4).	High capital cost relative to incumbent technologies, some materials are challenging to source ethically, recycling is challenging[50].	Cost and performance improvements through fundamental and applied research and scaling up of production. Some related technologies (e.g. Na-ion, LiS) are also promising.	Used battery remains could be hazardous. Recycling procedures not well established[59]. Cobalt is used in most Li-ion batteries[33], and its extraction is associated with serious human rights violations and environmental negligence[60]. ESOI = 10.

vi Significant potential in the EU and UK has been identified for PHS[98] and CAES[99].
vii The term ESOI = 'energy stored on investment', referring to the amount of energy stored over the lifetime of a storage device divided by the amount of energy used in producing that device, is used in this column, and described in more detail in the main text.

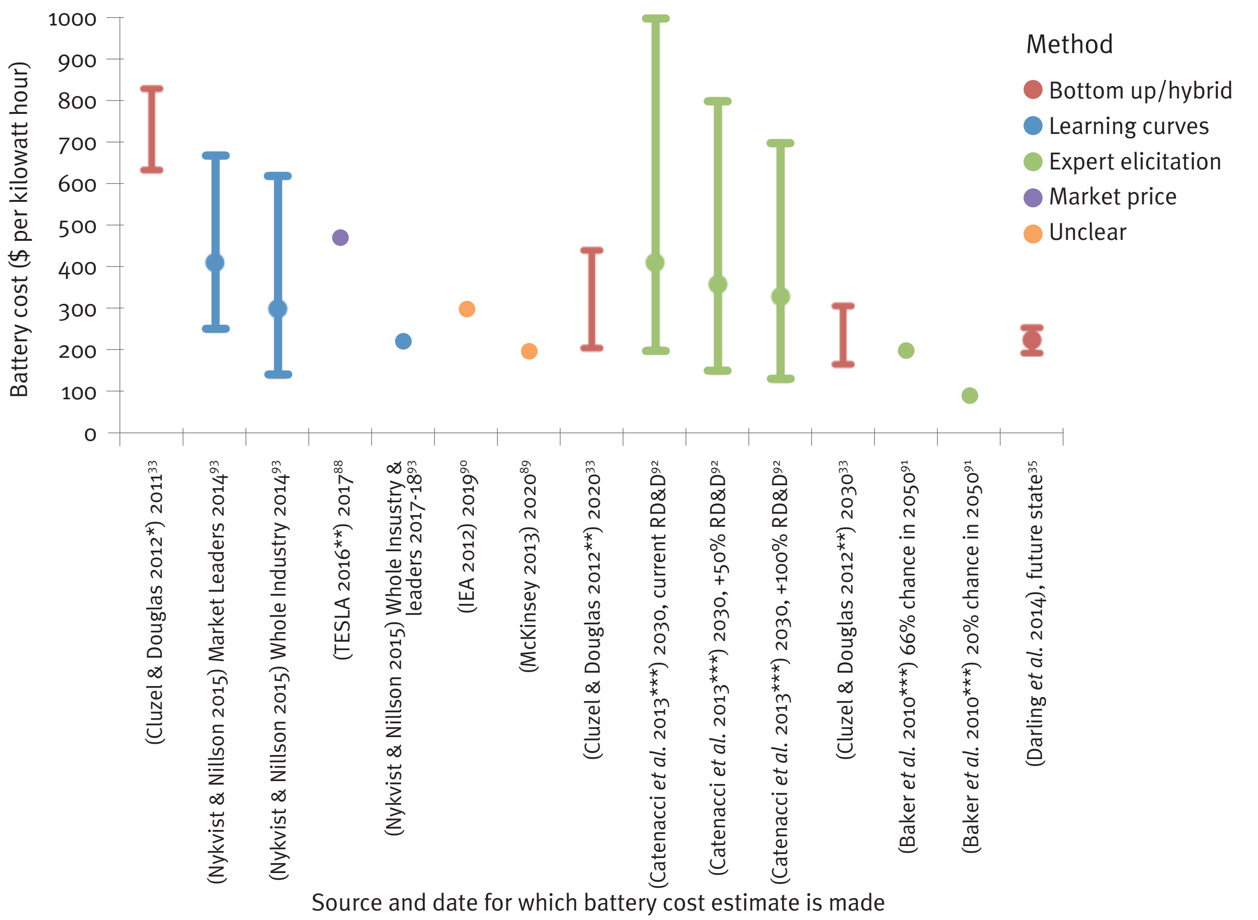
Appendix A: Overview of energy storage technologies (continued)

Technology	Technical Description	Key Variants	Deployment Status	Why is it promising?	What are its limitations?	Possible Future Developments	Environmental Impact
Lead-acid battery	An electrochemical device where lead and lead dioxide electrodes react with sulphuric acid during charge and perform the reverse reaction during discharge.	May be 'flooded' or 'sealed'. Flooded are cheaper, and longer lifetime, sealed require less maintenance and are safer. Flooded are more associated with stationary applications.	Mature. ~300GWh produced in the US alone[78,82].	Most mature and lowest capital cost electrochemical storage technology. Suitable for off-grid and micro-grid scale. Acceptable efficiency and fast response. Simple architecture gives recyclability[16,83].	Relatively low cycle life[16,78]. Toxic lead represents a serious issue when improperly recycled.	Significant cost saving developments unlikely. Early demonstration stage 'advanced' lead-acid batteries offer increased cycle life, but at higher cost and with a more complex battery architecture.	Lead is toxic and sulfuric acid is highly corrosive[77]. >95% recycling in Europe and USA, but a high incidence of lead poisoning is associated with informal recycling in the developing world[58,55–57]. ESOI = 2, low cycle life limits mitigation potential.
Redox-flow battery (RFB)	An electrochemical device in which liquid electrolyte, stored in two tanks, is pumped around a circuit, undergoing reversible chemical reactions during charge and discharge.	Vanadium redox flow batteries (VRFBs) are most mature. Zinc bromide hybrid flow batteries (ZFB) are also commercially available. Other chemistries are under fundamental research[81].	Worldwide grid-connected deployment: ~20 MW/49 MWh VRFB, ~1.0 MW/2.6MWh ZFB Additional capacity announced: ~28 MW/107MWh of VRFB, ~ 9 MW/232 MWh of ZFB[87].	Capable of operating at grid and off-grid scale, relatively high efficiency, fast response. VRFBs have very high cycle life, ZFBs have lower cycle life, but lower material cost.	Capital costs per capacity higher than competing technologies.	Scientific challenges remain in understanding flow and material behavior, understanding performance degradation, and selection of corrosion-resistant materials.	Vanadium has modest toxicity[81]. Recycling should be straightforward, but not well-established[57]. ESOI estimated at 3 for VRFBs, but higher life time estimates raise ESOI to above ten[16]. ESOI = 2 for ZFB.
High temperature, sodium-based batteries	An electrochemical device operating at above 250°C. Sodium ions flow to and from liquid sodium[85].	Sodium-sulphur (NaS) are most mature. Sodium-nickel-chloride (Na-Ni-Cl or Zebra) are also deployed. Similar performance.	NaS: 530 MW/3,700 MWh deployed, chiefly in Japan. NaNiCl: 18 MW/50 MWh demonstration installed[86,87].	Bulk storage that is not site-specific. Abundant, non-toxic materials. Relatively high cycle life[16,85].	Heating consumes power when not operational. Costly and slow to shut down/ start up.	Material developments could allow operation at lower temperatures, increasing cycle life, safety and flexibility.	Sodium and sulphur can react violently if faults occur[85]. ESOI = 6.

Box 4: How much will lithium-ion batteries cost in the future, and how do we know?

To give some idea of the state of research into the current and future costs of storage technologies, we outline some recent work relating to lithium-ion batteries. These batteries are a widespread and mature technology for portable electronic devices such as mobile phones and laptops. They became so within about 19 years of their invention, which is exceptionally fast for an energy technology[32]. However, lithium-ion batteries remain a niche technology for higher power, higher energy applications such as electric vehicles and stationary storage. A large amount of private sector investment is currently being put into scaling up and reducing the cost of lithium-ion batteries for these applications, and they are also the subject of a significant volume of academic research. Innovations are likely to arise from both routes.

Projections of future costs of lithium-ion batteries have been made using a number of different approaches, the quantitative results of which are summarised in the chart below. Note that these costs are specified for battery packs alone, and do not include peripheral components such as inverters and battery controllers, which are required to integrate with the grid or with other components in an off-grid electricity system.



Notes: *based on a 21-50kWh pack. **based on a 6.4kWh home battery system. ***averages of wide ranges.

Current and future estimates of lithium ion battery costs

Box 4: How much will lithium-ion batteries cost in the future, and how do we know? (continued)

Lithium-ion batteries for electric vehicles have been the focus of two 'expert elicitation' studies, which collate the opinions of a range of experts in the absence of reliable and authoritative data. In 2010, Baker *et al.*[87] interviewed academic and industrial battery experts in the US on the probabilities of lithium-ion batteries reaching a number of cost and technical performance thresholds by 2050, and the impact of increased R&D funding on these probabilities.

In 2013, Catenacci *et al.*[88] interviewed a series of policy and battery technology experts on how public research, development, and deployment (RD&D) funding in the EU should be divided between battery technologies, and between basic, applied, and demonstration funding for each technology, and on the range of possible electric vehicle battery costs that could be achieved by 2030, following a range of RD&D funding. Here, the expert responses indicated that funding should be spread across a range of technologies, and at a range of research, development, and deployment stages. In a scenario where the current level of investments in RD&D is maintained constant through 2030, roughly half of the experts expected battery cost between $200 and $400 per kilowatt hour for battery electric vehicles. The remaining experts provided more pessimistic projections.

In 2012, Cluzel and Douglas[33] published a detailed study of historical, current, and projected future lithium ion battery costs. The authors use a 'bottom-up' engineering model of battery cost and performance, which allows the design of a battery to meet given specifications based upon input data on cost and performance of materials and other components used. This bottom-up model is informed by expected future price trends in materials, cost savings associated with scaling up of production, and technological breakthroughs anticipated by battery experts. The authors conclude that improvements in fundamental chemistry and manufacturing improvements associated with scaling up of production are both likely to be important factors in battery development and cost improvement by 2020 and 2030.

Nykvist and Nilsson[94] recently published a report drawing together costs and prices of lithium-ion batteries from manufacturers and academic and industrial literature. They suggest that battery costs may already be below what many analysts have predicted in 2020, and even 2030. These results demonstrate a significant level of uncertainty in current and future costs, estimated market-leader costs below most 2020 projections, and a cost reduction rate that would result in battery costs of market leaders and the industry as a whole falling to $220 per kilowatt hour before 2020. However, whether such cost trends are sustainable is unclear, and some analysts have suggested they may be the result of an oversupply of lithium ion cells in anticipation of a larger future market for electric vehicles[95].

In summary, lithium-ion batteries could well cost in the range $130-600 per kilowatt hour by 2030, compared to today's cost of $250-800 per kilowatt hour. This significant reduction would be driven by increased volume of production, technical improvements and greater learning and automation in production.

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