Lloyd's Register
Foundation

Foresight review of energy storage

The key to safe, secure and sustainable energy systems

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About the Lloyd's Register Foundation

Our vision

Our vision is to be known worldwide as a leading supporter of engineering-related research, training and education, which makes a real difference in improving the safety of the critical infrastructure on which modern society relies. In support of this, we promote scientific excellence and act as a catalyst working with others to achieve maximum impact.

The Lloyd's Register Foundation charitable mission

- To secure for the benefit of the community high technical standards of design, manufacture, construction, maintenance, operation and performance for the purpose of enhancing the safety of life and property at sea, on land and in the air.
- The advancement of public education including within the transportation industries and any other engineering and technological disciplines.

About the Lloyd's Register Foundation Report Series

The aim of this Report Series is to openly disseminate information about the work that is being supported by the Lloyd's Register Foundation. It is hoped that these reports will provide insights for the research community and also inform wider debate in society about the engineering safety-related challenges being investigated by the Foundation.

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Contents

Executive summary

Our reliance on energy stretches from meeting our basic human needs to enabling the technologically advanced world that we live in. We use energy to keep us warm or cool us down; it powers infrastructure to provide water, food, healthcare, transportation and communication. The energy we depend upon is mainly generated by converting stored chemical energy into energy that we actually use. The stored energy we are very familiar with is fossil fuels, such as gas, oil, coal, or renewable sources, such as wood. Our demand for energy is growing at the same time that the world is looking to decarbonise.

This review explores the role of energy storage and how it can impact the safety of life and property around the world. Energy storage does not stand alone: it is part of energy systems which are integral to the infrastructures that ensure our individual and communal safety.

Energy storage is a key enabling technology for low carbon power, transport and heating infrastructures. By facilitating better use of renewable sources, disruptive system infrastructure upgrades can be postponed. For critical systems, a vital autonomy is afforded, enabling these services to continue to function during critical events. Thermal storage allows us to make use of waste heat and cold, and can be integrated into delivery chains, protecting food and medicine. The energy systems enabled by storage provide remote communities or developing nations with the opportunity to leapfrog costly infrastructure development.

The review describes the different forms of low carbon energy storage that currently exist and highlights how the choice of energy storage used is very much dependent on the application. The battery that powers your mobile phone could be combined with many others to store excess energy to power a city, but this may not be the safest or most efficient way to store and release the energy when needed. The review considers the application of energy storage through the lens of safety and the opportunities and threats to safety that are associated with the use of low carbon energy storage.

In assessing the safety aspects of these new forms of energy storage, it is important to remember that fossil fuels themselves are not inherently safe, being flammable, environmentally damaging and at the heart of many accidents. The risks are largely addressed through engineering and operational management. We accept these risks in our everyday life because of the essential role that such energy systems play.

Furthermore, recent research highlights the fact that fossil fuel emissions not only alter the world's climate, but also pose serious health risks. Cleaner, more sustainable options are therefore consistent with long-term safety.

However, the use of more low carbon energy sources and, in particular, renewable electricity generation, may create new challenges for delivering reliable system operation - with associated impacts on safety - for example solar power is not generated at night. Energy storage technologies can restore this reliability and hence will be increasingly required as the grid decarbonises.

Energy storage devices can contain hazardous chemicals, which need to be safely sourced, contained, transported and disposed of. The complexity of existing systems is increased by the integration of storage, potentially making it harder to predict and manage failures. This impacts first and second responders*, as well as installers and other operators, who need to understand how to manage the new hazards. Considerations for secondary markets need to be addressed, to prevent unexpected hazards being exported to other owners or countries.

Safety and sustainability can be incorporated into the design of energy storage devices and systems to mitigate many of the risks. Safety engineering can be applied to all stages of the device's manufacture and use, and standards can provide guidance for best practice. Infrastructure planning, which takes all components of the system, local resources and requirements into account, can allow the most effective deployment of the technology. The location of energy storage and the degree to which it should be either distributed or centralised can impact safety as well as cost.

Through this review, the Foundation is informing public debate about the low carbon energy storage technologies that will become more embedded into the infrastructure on which we depend. It provides a balanced view on the risks and opportunities these new technologies bring and sets out what is needed to safely adopt these technologies and avoid creating a new set of hazards. The review has highlighted the following as priority areas in energy storage:

- storage systems support
- through-life safety and sustainability
- public engagement, skills and knowledge
- maximising value from demonstrators.

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* see glossary page 53

Foreword

For many of those who pick up this review for the first time, energy storage is something that is associated with batteries that power mobile phones, laptops or even cars. In reality, much of the energy we use comes from energy stored in coal, gas, oil, wood or uranium.

The selection of energy storage as the subject of this foresight review is driven by the increased demand for energy storage to drive a reduction in carbon emissions, provide energy to those that would otherwise not have access to energy, and increase the resilience of critical infrastructure.

As we collectively move to renewable sources of energy, we find that these are only available when the generating conditions are right: solar power is only available during daylight hours; wind power is only available when the wind blows. To maintain a constant supply of power, particularly low carbon power, there is a need to store excess renewable energy and release this for use when and where it is needed.

A combination of energy storage and renewable power can provide access to energy to those who would otherwise not have access to it. Access to lighting, heating, cooling and communication can result in life-changing impacts.

Stored energy also plays an important role in increasing resilience. As an example, using cold liquids, solids and gasses to maintain refrigeration of medicines or foods means that there is no need to rely upon, or have backups for, electricity supplies.

The introduction of new energy storage solutions can bring with it significant improvements to safety. However, we must also remember that there are risks associated with energy storage technology and these need to be addressed early to result in safe access to energy.

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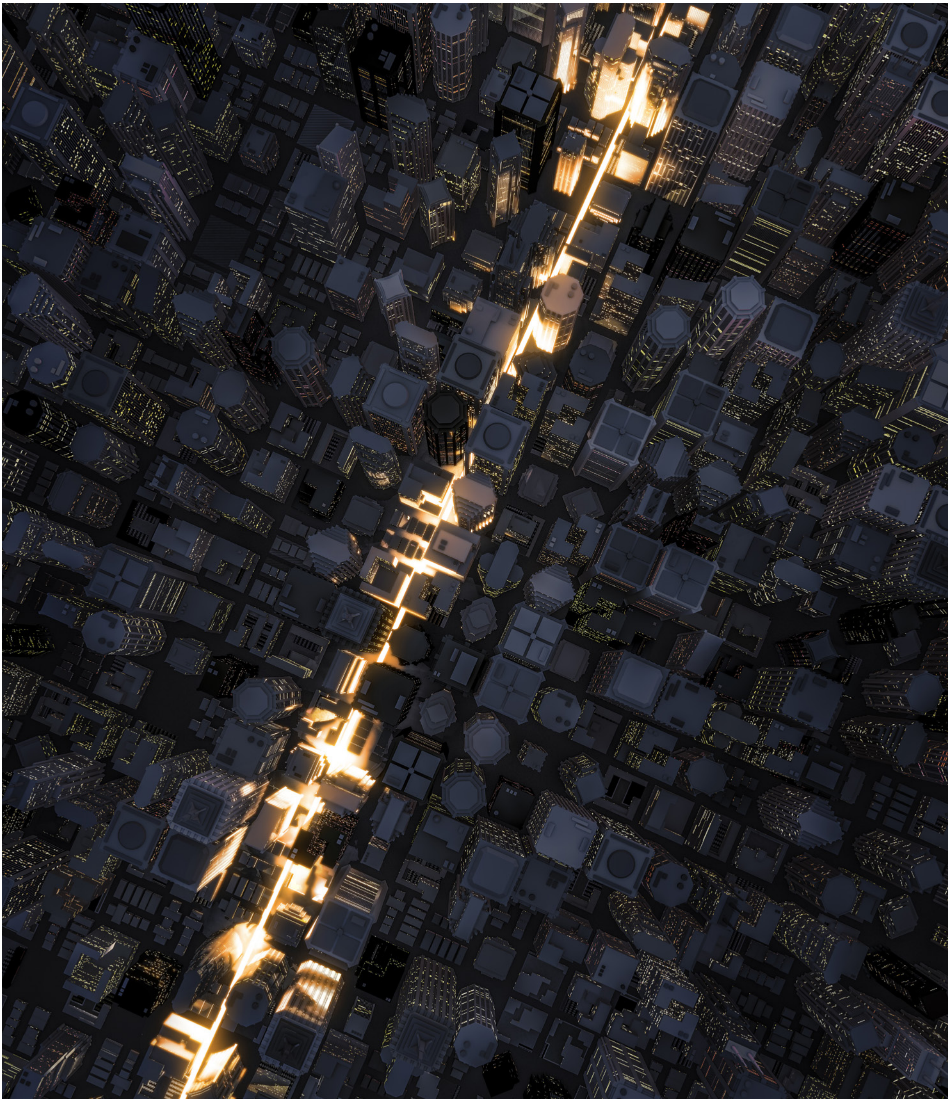

Background

This report is the sixth in a series commissioned by Lloyd’s Register Foundation as part of its emerging technologies research theme. It looks forward at how developments in the area of energy storage might impact the safety and performance of the engineered assets and infrastructures on which modern society relies.

Lloyd’s Register Foundation is a charity and owner of Lloyd’s Register Group Limited (LR). LR is a 257 year old organisation providing independent assurance and expert advice to companies operating high-risk, capitally intensive assets primarily in the energy, maritime and transportation sectors. It also serves a wide range of sectors with distributed assets and complex supply chains such as the food, healthcare, automotive and manufacturing sectors.

Building on the findings of this review, the Foundation will look to identify aspects of energy storage that might provide opportunities or threats to safety, in line with its charitable objectives, and where the Foundation might focus its research and other grant giving to make a distinctive, positive impact.

The Foundation is a charity with a global role. Reflecting this, the principal authors identified an international expert panel comprising of industry, academia, government, regulators and representative bodies. The panel assembled in London in November 2016 for a two day workshop to consider the review from these various perspectives. The findings of the workshop were circulated to the panel and also to those that had expressed an interest in attending the workshop but were unable to do so. This report contains the output and findings from the panel and the consultation.

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Why do we need energy storage?

As a society, we rely on energy in many forms to provide the essentials for life, from heating to more advanced infrastructures such as electricity, transportation or mobile telecommunications. For the most part this energy comes from a stored form, most commonly as hydrocarbons such as oil, gas, coal and wood. Our drive towards low carbon energy systems while continuing to meet the needs of society - such as clean water, food, heating and cooling, light and power as well as supporting our modern transport, medical and communications infrastructure - is the main reason behind the increasing interest in energy storage today.

Energy storage is most familiar to many of us as the batteries which have transformed modern portable devices, such as laptops and mobile phones. The mobility and flexibility that these devices have afforded us has been, to a large degree, enabled by their onboard store of energy, allowing extended periods of use without direct connection to the grid. We are now seeing this scaled up to enable the electrification and decarbonisation of larger and more complex systems. An example of this is electric and hybrid vehicles, where stored electric energy is converted into propulsion (ie kinetic energy). The choice of energy storage technology for mobile applications is often constrained by the need for it to be as light as possible and occupy the smallest volume, whereas energy storage systems for fixed grid applications are less restricted by weight or volume.

Energy storage allows us to store energy during times of abundant supply for later use, when availability of energy is limited or demand exceeds supply (see figure 1 overleaf). For example, the UK grid is facing unprecedented challenges in its drive to meet the requirements of clean, sustainable and resilient energy. A transformation of the whole system is called for by the global challenges of climate change, embodied in the UK's commitment to reduce its greenhouse gas emissions, by at least 80% of 1990 levels by 2050, and the UN's Sustainable Development Goals, essential for meeting the growing needs of an expanding and developing population. In order to meet these challenges efficiently, safely and resiliently, while also addressing the national and international need to reduce energy poverty, new markets and business models, as well as new system operating paradigms, will need to be developed.

Decarbonisation of any energy system requires greater dependence on renewable energy generation*, such as solar, wind and tidal, as well reduced consumption of fossil fuels by the heat and transport sectors. However, renewable energy sources are often dependent on the weather (sun, wind) and are not always available on demand. To cover periods of low renewables availability, either backup power generation or energy storage is required. Whole systems analysis* shows that the integration of storage leads to the greatest savings.

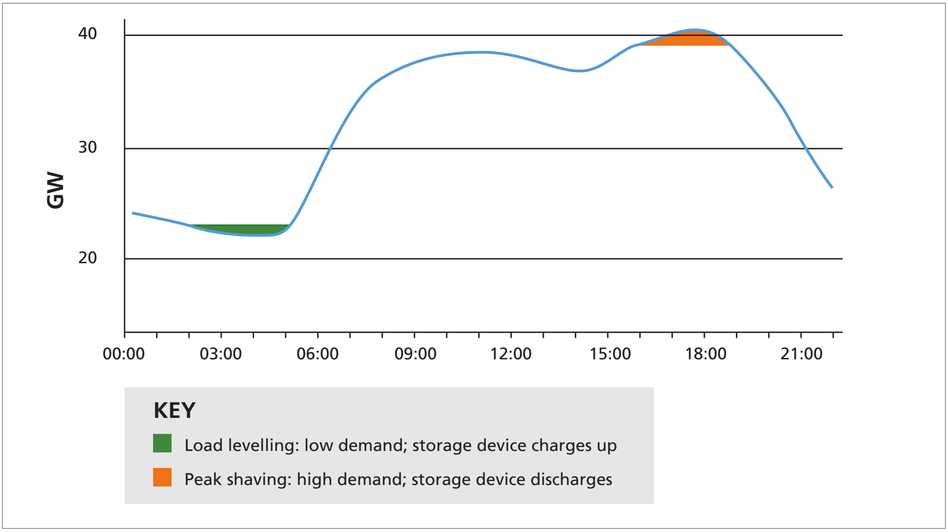

Figure 1: The winter demand profile for the UK shows low demand in the early morning and high demand in the evening. Energy storage can level out the demand profile by charging up when the demand is low and supplying power when the demand rises above a defined level [Source: National Grid, 2015].

* see glossary page 53

Storage allows home owners with solar panels to make the best use of their investment, by allowing them to use the energy their panels generate during the day at a time more convenient to them, usually in the evening. For communities with poor or no access to energy grids, or for critical services which require absolute reliability, microgrids which integrate storage allow them greater autonomy. Microgrids are local smart grids containing all the essential features of a traditional grid, enabling them to run independently.

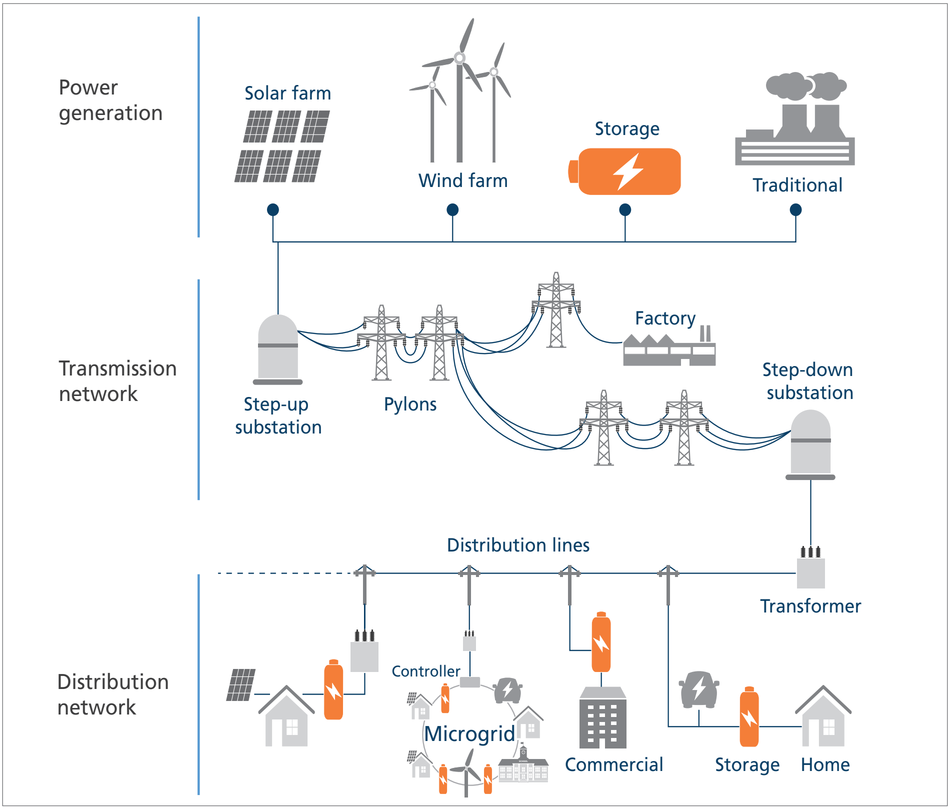

Figure 2: A typical nationwide electricity grid and possible storage locations. The microgrid shows the sort of system which could be developed for communities in countries lacking a nationwide grid. These can be connected up later to form such a grid.

Case study 1 - Islanding*

Orkney, the living laboratory

Islands, having absolute boundaries and harsh conditions, represent an opportunity to test not only specific energy storage technologies but also mechanisms for integrating these into a whole energy system, as well as a range of operating paradigms. Orkney has the highest proportion of households generating their own electricity of anywhere in the UK and more than 100% of the total electricity needs of the entire island is generated from renewable energy, including wind, tidal and wave. However, the electrical grid on Orkney is only weakly connected to the UK mainland grid and does not integrate with transport and heat systems, which could soak up excess energy to reduce the load on the system. Therefore, up to 60% of the renewable generation may need to be constrained when generation exceeds demand, representing an annual loss of more than £4 million to the local economy.

Orkney benefits from a highly engaged community, from consumers to council. The Heriot Watt Orkney Energy Storage Accelerator works in partnership with the Orkney community, government, development agencies and a diverse range of renewable energy innovators and businesses. It aims to supply all energy needs through a fully integrated renewable energy system, creating a demonstration bed for analysing and benchmarking new technologies, policies, market frameworks and consumer engagement to maximise resilience and efficiency. Orkney is therefore a living laboratory for identifying the opportunities and challenges associated with operating such a system and assessing the impact that a range of energy storage technologies, such as hydrogen and batteries, will have. The lessons learned here can be applied to the development of UK and global energy systems. There are other islands developing similar systems, such as Barbados in the Caribbean and T'au, an island in American Samoa.

* see glossary page 53

What is energy storage?

Energy exists in many forms, some very familiar to us, such as electricity and heat. It can also be stored in many forms, such as the chemical bonds in fuels or gravitational potential, where raised objects or liquids are allowed to fall, driving machinery to release energy when required.

In order to store energy, it must often be converted from its usable form, such as electricity, to a storable form, such as electrochemical energy stored in batteries. It is important to note that conversion of energy from one form to another always involves losses and that all storage mechanisms 'leak' stored energy to a certain degree. Although the process of storing energy always wastes some of the energy it preserves, it is useful for balancing times when energy is abundant against times when it is scarce, or for providing energy for mobile or off-grid applications. We can summarise energy storage as the ability to store energy and use it when and where it is needed.

The form and amount of energy required, as well as the length of time for which it is needed, varies greatly with application. Each technology has different storage capacities, defined by the total amount of energy they can hold, measured in watt-hours (Wh) - the size of the 'energy tank'. The amount of energy they can release at any moment varies too, defined as the store's power, measured in watts (W) - the rate at which the 'energy tank' can be filled or emptied. For example, a 20 MWh store delivering 2 megawatts of power will last for 10 hours (a megawatt [MW] is 1 million watts). Electricity storage systems need to store enough energy to last through 'blackout' periods and also be able to deliver that energy fast enough to meet electrical demand (also known as load*). In addition, energy storage devices need to store energy efficiently. The ratio of energy used to fully charge the store to energy released in a full discharge is the round-trip efficiency*, used to compare the effectiveness of various technologies.

Energy storage technologies can best be classified by the form in which they store energy, and several storage technologies are briefly described within this framework on the following pages. As energy storage is both a broad and emerging field, this list is intended to be illustrative, rather than exhaustive.

Power-to-X

Power-to-X refers to technologies that convert surplus electricity into useful products, usually through electrolysis, using the electrical current to break chemical bonds, such as splitting water into hydrogen and oxygen. For example, power-to-gas energy storage generates a gaseous fuel, such as hydrogen or methane; power-to-liquid converts hydrogen into methanol (a liquid fuel). The X can also stand for one of the following energy vectors*: fuel, ammonia, chemicals, heat, mobility and syngas*, among others.

Power-to-X pathways allow power from the electricity sector to be used in other sectors, such as transport, heat, the gas grid and industrial processes. They vary in their efficiency and the choice of power-to-X in any location depends on the desirability of the end product. The most efficient form, requiring the fewest conversion steps, is power-to-gas, in which gaseous hydrogen is produced and either stored for use on site or injected into a gas grid for direct use. There are two key advantages to this option: gas can be stored for long periods and disruption is minimised by utilising existing infrastructure. However, the legislated amount of hydrogen which can be injected into the grid is currently limited. As modification is needed to enable higher amounts of hydrogen to be distributed, other pathways have been developed.

Electrical

Capacitors and supercapacitors (sometimes called ultracapacitors) can store electrical energy without the need for conversion to another form of energy. This makes these devices efficient with very fast response times, however they can only store energy for very short periods. They are used in short-term, rapid charge/discharge applications, such as energy recovery from braking in vehicles. Supercapacitors hold less energy per unit weight than batteries, but they can deliver their energy rapidly and can tolerate many more charge/discharge cycles. The Gangnam District of Seoul, South Korea, has introduced about 400 supercapacitor powered buses since February 2014 and is aiming to reach 3,500, half of Seoul's bus fleet, through a phased introduction by 2020.

Superconducting magnetic energy storage (SMES) devices consist of a coil of a superconducting material cryogenically cooled to a temperature low enough to permit superconductivity*. When electrical current is passed through the superconducting coil, it generates a magnetic field which can store the energy indefinitely, as long as the device is kept sufficiently cold. Sustaining such low temperatures uses up a lot of energy and research is underway to find superconducting materials which can operate at higher temperatures, thereby improving the efficiency of these devices.

Electrochemical

A rechargeable battery consists of several electrochemical cells, each having two electrodes, a cathode and an anode, both surrounded by an electrolyte. The electrolyte allows the movement of charge carriers, such as lithium ions in the well-known lithium-ion (Li-ion) battery, familiar through its widespread use in laptops, mobile phones and other portable devices. When the battery charges, an electrical current causes the positively charged lithium ions to move from the cathode to the anode. This process is reversed when the battery is in use. Li-ion batteries are characterised by having the highest energy density* among commonly used battery types, though still well below those of liquid fuels such as gasoline.

The high energy density of batteries makes them an attractive option for onboard storage in mobile applications, such as automotive and unmanned aerial vehicles (UAVs). Plug-in electric vehicles and hybrids could be considered as a pool of distributed storage and vehicle-to-grid schemes are being developed to assess the viability of using car batteries for grid support.

Flow batteries, also called redox flow batteries (RFBs), offer an alternative storage technology which can be scaled up for grid scale applications. During charge and discharge, the electrolyte solution flows past a membrane which allows ions to exchange. The energy storage capacity of a flow battery is limited only by the volume of the tanks holding the electrolyte. RFBs have long lifetimes* and can tolerate their energy being almost completely drained. They are commercially available, but cost reductions through further research are expected.

Fuel cells generate electricity from the chemical energy stored in a fuel by reacting it with oxygen. They require a continuous source of fuel and oxygen to keep the reaction going. They therefore do not charge and discharge in the way that other technologies do, but continuously produce electricity while the fuel (the energy store) and oxygen are available. Electrolysers operate like fuel cells in reverse, using an electrical current to produce fuel (see power-to-X on page 12).

* see glossary page 53

Chemical

Energy is stored as chemical potential energy in the bonds of molecules. Most of the fuels with which we are familiar, such as oil, gas, diesel, alcohols and sugars are of biological origin and can technically be classed as chemical energy storage. However, as these do not necessarily support decarbonisation, they are not included in this report. Instead, low carbon fuels such as hydrogen, hydrogen peroxide and ammonia, as well as synthetic fuels, such as methane and methanol, which can be considered to reduce carbon emissions by reusing captured carbon, are covered here.

Hydrogen and its storage are of particular interest, as it is a carbon-free fuel providing opportunities to drastically reduce carbon emissions. However, hydrogen needs to be handled carefully and special safety precautions are needed. It is perceived as being particularly hazardous, but has been widely used in industrial processes for many decades. Thus the risks are well understood and can be mitigated through application of safety procedures, developed over years of experience. Consequently, more than 270 hydrogen refuelling stations have been operational around the world since 2000, without incident.

Hydrogen holds three times the amount of energy held by an equivalent mass of petrol, but is difficult to store in the gaseous state, occupying a large volume. For grid scale storage, suitable underground spaces can be used to store hydrogen at moderate pressures. For mobile applications, denser storage is necessary and current hydrogen stores for transport applications use high pressure (up to 700 times atmospheric pressure) tanks of gaseous hydrogen.

Mechanical (kinetic energy)

Electrical energy can be converted into and stored as kinetic energy using a range of mechanical devices, including flywheels, hydraulics, reciprocating engines and compression systems. These devices can be reversed to convert the kinetic energy back into electrical when required.

Compressed air energy storage (CAES) has been used for peak shaving* (see figure 1, page 9) since the 1970s and is suitable for both large and small scale applications. Excess energy is used to compress air, which can be stored in underground salt caverns to reach capacities of over 1,000 GWh, or in high pressure tanks for smaller scale storage needs. To release the energy, the compressed air can be allowed to expand, driving gas turbines* to generate electricity. CAES can be a low cost option with no polluting or toxic chemicals and has long lifetimes and reasonable efficiencies, especially if the heat generated by the compression/charging process can be stored and used to assist in the expansion/discharging process.

Flywheels store energy as rotational energy. To store the energy, a rotor/flywheel is accelerated by applying a force. The rotor spins with a high momentum, resisting changes in rotational speed. If friction is kept to a minimum, this rotational energy can be stored until a later stage, when it can be applied to a mechanical load, converting the energy into a usable form and decelerating the rotor. The amount of energy stored in the flywheel is defined by the rotational speed, which is limited by the strength of the materials used to construct the rotor. As it is impossible to avoid all friction losses, the spinning rotor will slowly lose energy if the accelerating force is removed. Advanced flywheels are made of carbon fibre composite materials and use magnetic bearings to suspend the rotor in a vacuum, reducing friction to a minimum.

Gravitational potential

Water or solid masses can be elevated by electric motors, storing energy in the form of gravitational potential. When these are released at a later stage their weight causes them to fall or push downwards. This energy can be used to drive turbines to generate electricity.

Pumped hydro energy storage (PHES) is the oldest and most extensive form of energy storage in use in our electricity grids today and has very high capacities. When excess electricity is available, water is pumped uphill and stored in a reservoir. When electricity demand exceeds supply, the water is released to flow downhill, driving turbines to generate electricity. Ffestiniog, completed in Wales in 1963, and the Guangdong Pumped Storage Power Station in China, completed in 2000, are two examples of this form of energy storage. While suitable locations for PHES are currently limited and can be environmentally disruptive, due to the

* see glossary page 53

The Srinagarind Dam in Thailand has a rated power of 720 MW, half of which is pumped storage. The annual generation is 1,160 GWh.

need for two large reservoirs at different elevations, new possibilities are being explored for siting the lower reservoir underground. Abandoned mines and caverns are possible candidates, which could be developed reasonably quickly.

Tidal lagoons can be used to generate hydroelectricity from trapped tidal water, where the turbines are built into the lagoon wall. Similar to PHES, here the tide itself refills the energy storage 'reservoir'. There are several sites around Britain's coasts which are suitable for this technology, early forms of which were in use by the Vikings.

However, considering the increasing demand for clean water, solutions which make use of solid materials may be more sustainable. In the US, Energy Cache is investigating the use of buckets of gravel on a line, which are raised or lowered using ski lifts to store and release energy respectively. Advanced Rail Energy Storage (ARES) use decommissioned rail tracks to move concrete-filled rail carts up and down to achieve the same effect.

Thermal

Thermal energy storage includes thermomechanical and thermochemical technologies. Liquid air energy storage (LAES) is an example of a storage technology which involves both thermal and mechanical storage. When energy is abundant, air is drawn in and stripped of its CO_2 and water vapour, both of which would be unable to flow through the pipes at cryogenic temperatures, as they freeze to the solid state. The remaining constituent of air is mostly nitrogen, which condenses down to a liquid when cooled to -196°C and can be stored in large tanks. When the stored energy is required, the liquid is heated up to room temperature, causing it to evaporate and expand into the gaseous form, driving turbines. The cold air can be passed over gravel tanks during the expansion process, allowing the cold to be 'stored' to assist in liquefying air during the next charge cycle. If the process is also integrated with industrial processes, which produce large amounts of waste heat and cold, the efficiency of this energy storage system can reach 70%. Other gases and liquids can be condensed and expanded in a similar fashion. This class of technology is often referred to as cryogenic* energy storage due to the extremely low storage temperatures required.

Pumped thermal energy storage (PTES) uses two large storage tanks – one for cold and the other for heat. Electricity is used to drive a heat pump*, which transfers heat from the cold store to the hot store. The greater the temperature difference between the two, the more energy is stored. The heat pump can operate in reverse as a heat engine, releasing the energy as electricity. If waste heat and cold during the charge and discharge processes is carefully conserved, PTES can achieve round-trip efficiencies of 70%. Refrigerators work in similar ways and can therefore be considered as a mechanism for distributed energy storage.

Materials able to absorb/release a lot of energy without changing phase, such as water, molten salts and gravel or bricks, store energy as sensible heat*. Liquid forms are particularly useful, as they can be used to transfer heat from one process to another, enabling the efficiency improvements used by many energy storage technologies. Steam, water and oil are commonly used as storage media in the electrification of domestic heating. Storage heaters use bricks to store thermal energy absorbed during times of low electricity demand, when prices are cheaper. Concentrated solar power plants make use of oils and molten salts to store the considerable solar energy they absorb and intensify. An ice storage system called the Ice Bear freezes water using surplus electricity and uses the stored ice to cool buildings during peak hours.

The energy stored in thermochemical energy storage (TCES) relates to interactions between molecules in all three phases of matter, such as adsorption, where gas molecules stick to the surface of solids, and bonding between gas and solid molecules to make new chemicals. This technology is in the early stages of research, but has the potential for the highest energy density of all the thermal storage technologies.

Summary

In conclusion, it can be seen that there are many different energy storage options available, with more being developed. These have different advantages for different applications. While the future role of energy storage continues to evolve, what is clear is that it is not likely that one technology will meet all our energy storage requirements, but rather a portfolio will be used for the range of applications and purposes needed.

* see glossary page 53

How can energy storage enhance safety?

Here we explore the roles of energy storage in enhancing safety of the critical infrastructures on which society depends.

Chemical energy storage, in the form of fossil fuels, is an integral part of current energy systems and there are many examples of risks and hazards associated with these that have been reported over the years, such as explosions from gas leaks, the destruction of local ecosystems and water supplies by oil spills, as well as air pollution from vehicles and diesel generators. Recent research indicates that as many as 7 million premature deaths annually can be attributed to air polluted by vehicle and power supply emissions (WHO, 2014). New energy storage technologies provide an opportunity to build a safer, cleaner world with greatly reduced dependence on fossil fuels.

Low carbon energy storage is now common in modern society, primarily through the role of batteries for a wide variety of devices, be these consumer devices such as mobile phones, tablets and laptops, or commercial devices such as solar powered lighting. In this sense, energy storage is already at the heart of modern communications and data management, as well as supporting the roll-out of off-grid electrical devices, with the associated safety and societal benefits these bring.

But the focus of this review is on the roles of energy storage in enhancing safety of the critical infrastructures on which society depends.

Mobility

Electric machines are usually more efficient, quieter, more reliable and simpler to maintain than mechanical machines. When electricity from low carbon sources is used to power a hybrid or fully electric vehicle, efficiency is significantly enhanced, carbon emissions and noise levels are reduced and local air quality in towns and cities is greatly improved.

Electric-based transport solutions are not new: electric trains and trams are widely deployed throughout the world. Electric machines can also power electric bikes and scooters, buses, delivery fleets, shipping, rail, unmanned aerial vehicles (UAVs) and aircraft. While charging the battery for electric vehicles has the potential to increase peak demand for electricity, fuel cell electric vehicles are powered by hydrogen, which could be generated during times of low demand.

Energy storage plays a key role in the electrification of transport applications by providing onboard energy in the form of batteries or low-carbon fuels, such as hydrogen or methanol, allowing transport systems to function independently from an energy grid. For public transport systems this avoids the need for costly electrified lines, their maintenance and the risks inherent to this.

Robotic and autonomous systems (RAS) can play significant roles in enhancing safety. As an example, RAS can be used to inspect infrastructure assets such as bridges or pipelines by physically monitoring with cameras or other sensors. RAS require stored energy to operate remotely, be that flying, swimming, climbing, filming, sending data, etc. The information collected by the RAS is needed to assure the asset's safety, therefore they need to be operational when needed and the stored energy needs to be sufficient for the RAS to complete its mission. Current storage technologies can lead to designs that allow significant function but over short time periods or reduced function over longer durations. Improvements in power duration while ensuring low weight could increase the potential benefits from RAS. For operation in explosive environments, it is essential that all components of RAS be rigorously tested to ensure that they cannot trigger an explosion. Triggers can include sparks, flames or high temperatures.

Heat and cold

The provision of heat and cold plays a critical role in sustaining a healthy human population in many parts of the world. Extreme temperature events are expected to be more common as the world's climate changes (Huang, 2011) and have caused globally more than 155,000 premature deaths since 2003 (CRED, 2017). Similarly, the ability to keep perishable food, goods and medicines cold during transport and storage plays a vital role in both local and global supply chains, minimising food waste and ensuring that medical care is widely available (see case study 2 on page 23).

The storage of heat in cold regions provides a buffer in the case of heating system failure, for example through power loss. Increasing emphasis is being placed on engineering heat and cold energy storage, as well as better heat integration incorporating waste heat where possible, to reduce overall energy demand* in a range of applications, including the built environment and transport.

* see glossary page 53

Power resilience

Energy storage offers the advantage that some energy is always available, even when the primary supply is lost. This continuity of energy supply offers significant safety benefits, by reducing risk to life and property. In this way, energy storage can enhance safety at the local level of an individual household, a community, an asset, or at the national level, supporting a more resilient supply. Replacing diesel generators with storage systems to back up on-site renewable generation, such as solar photovoltaics (PV), will remove the need for ongoing purchase and storage of fuel, an important consideration in countries where fuel is scarce or expensive and may additionally be at risk of theft.

The following benefits could be realised through the greater uptake of energy storage in the electricity infrastructure.

- Increased resilience across the whole energy system, ensuring that minimum function is always available. Resilience is enhanced by incorporating redundancy in the system, minimising single point failures.
- The ability to create energy islands, allowing operation independently from a national infrastructure. Islanding of critical services allows them to continue to operate if other parts of the system go down.
- Enables longer periods of backup power, providing more time to react to disruptive events.
- With increased penetration of renewable energy generation, risk of power loss occurs due to variability of wind, sun, etc. Energy storage can be used to balance supply in place of generation from gas and oil.
- More efficient use of assets that generate energy, such as solar and wind farms, storing surplus energy and deploying this when needed. This minimises the need for fossil energy backup systems, helping to reduce costs and achieve carbon reduction targets.

Environment and sustainability

A key driver for the uptake of energy storage is its role in supporting the transition towards a lower carbon and cleaner economy. Specific additional environmental benefits associated with the uptake of energy storage are given below.

- Energy storage solutions such as batteries are much cleaner, in terms of air quality, than current solutions for delivering a reliable energy system, such as backup diesel generators.
- The reduced need for investment in electrical distribution infrastructure will also limit visible pollution from wires, pylons etc, as well as reduce the disruption and cost associated with their construction and maintenance.

- Energy systems with integrated storage offer the potential for developing nations to avoid the need for a national energy infrastructure, instead moving directly to a distributed energy system.
- By supporting the transition from fossil fuels to clean energy, the need to produce and move oil and gas is also reduced. This will reduce the opportunities for oil spills and leaks from pipelines.
- The widespread availability of transportable energy storage solutions enables faster response to disastrous events.
- Energy storage is key to the development of automated monitoring of critical infrastructure, for example through sensors, drones or robotics, improving safety.
- Re-use (second life*) of batteries which no longer meet all the requirements for their primary applications, but are still functioning. For example, when an electric car battery can only store 80% of its original energy capacity it is considered unsuitable for powering a vehicle but can be repurposed for grid support.

Case study 2 - No 'one size fits all' solution

When selecting an energy storage technology to deploy for a particular application it is important to match the features of the technology to the services it is required to deliver. Below and overleaf are two sample applications illustrating the importance of deploying the appropriate technology, storing energy in the required form and avoiding conversion losses.

Backing up solar

Solar panels convert sunlight to direct current (DC) electricity. A technology which stores this energy electrically or electrochemically, such as batteries, supercapacitors and flow batteries, offers efficiency benefits by storing the energy in an appropriate form. Similarly, the energy can be easily and rapidly released as electricity for grid support services.

Batteries, in particular Li-ion batteries, have high energy densities and are therefore suitable candidates for residential storage where space is limited. There are a growing number of planning applications for solar PV projects with co-located battery storage and the emergence of a market for residential batteries to store the energy from rooftop solar panels further supports the idea that batteries are a suitable match for these applications. However, their end-of-life disposal can present sustainability and environmental problems if not properly addressed.

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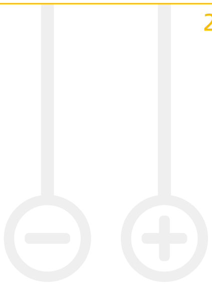
* see glossary page 53

Case study 2 - No ‘one size fits all’ solution

Minimising food waste

The Food and Agriculture Organization of the United Nations estimates that 30-40% of total food production in developing economies is lost before it reaches the market. Many valuable resources, such as fresh water, land and energy, are used to produce food which is desperately needed to feed our growing population. In addition, food that is left to decay releases methane, a gas having 23 times the global warming potential of CO_2. Minimising waste is therefore essential to ensure that sufficient food is produced efficiently and with fewer emissions.

A large proportion of food loss and degradation*, particularly for livestock products, fish, fruit and vegetables, is due to poor temperature control during storage and transport. Improving refrigeration standards across the whole food production and delivery chain can reduce food waste and have many benefits. For example, fresher food is healthier and provides more nutrients to the consumer and farmers can sell a larger proportion of their produce.



The Dearman engine runs on liquid air or nitrogen and can operate as a zero emission and highly efficient transport refrigeration unit (TRU) for delivery vehicles and shipping containers. When liquid air or nitrogen is brought into contact with the refrigeration compartment, the compartment and its contents are cooled while the cryogen heats and expands by about 700 times, greatly increasing the pressure and driving the engine. A heat exchange fluid*, such as antifreeze, is used to speed up heat transfer within the engine, improving its efficiency.

Liquid nitrogen is used in many industrial processes and commercially produced in large quantities, with a significant surplus available for use. Liquid air or nitrogen can also be produced using off-peak electricity and stored cryogenically (-196°C) in unpressurised insulated vessels, which can be stationary or distributed to remote locations through established tanker and shipping networks. The development of a liquid air economy is both technically and economically feasible and would enable cold infrastructures badly needed in many developing countries, and particularly in the context of a warming world, for the preservation of food and medicines, as well as for air conditioning. In addition, this technology has the unique ability to capture low grade waste heat* (up to 150°C) at high efficiency from industrial processes and intensive computing. Liquid air-driven engines can displace their diesel counterparts, reducing well-to-wheel CO_2 emissions, noise and air pollution. Liquid air is a thermal energy store having a unique set of attributes suitable for a robust low carbon power and transport infrastructure and especially appropriate for integrated heating or cooling requirements.

* see glossary page 53

Summary

In conclusion, energy storage can lead to improved safety through the introduction of more reliable systems that enable transportation, safety monitoring of infrastructure and safer delivery of food and medicines, offering solutions that are less polluting and more sustainable than the options in common use today.

What threats to safety could energy storage introduce?

While there are clear benefits to adopting energy storage, as for most technologies there is the potential for safety to be compromised. For example, batteries for energy storage are already widely applied in consumer devices and hence familiar to consumers, but recent safety issues such as the Samsung Galaxy Note 7 and the Boeing 787 Dreamliner fires have highlighted the potential risks associated with energy dense storage technologies. The consequence of such failures on safety could become even more significant when dealing with tens of kWh batteries in a car, or hundreds to thousands of kWh energy stores for grid scale storage. The safety compromises are considered in the following sections.

While there are clear benefits to adopting energy storage, as for most technologies there is the potential for safety to be compromised.

Transport infrastructure

Transport industries (which include road, rail, air and sea) are looking to energy storage to reduce emissions, improve efficiency and increase resilience. For many of these industries, the vehicle must carry all the energy that it requires or be connected to an energy grid. All have restrictions on the volume that energy storage can occupy and varying requirements on weight (for example aircraft require lightweight energy storage but for ships the weight of energy storage may be considered as ballast). Substituting existing solutions with energy storage brings with it new risks that need to be understood and managed.

Sometimes threats to safety can be exaggerated through public perception. Hydrogen, for example, is commonly considered to be a dangerous explosive gas. Yet industry has been working safely with hydrogen for many years and this knowledge is incorporated into energy storage systems. Acceptance of this technology will therefore depend upon the public perception of risk.

The examples on the following pages highlight some of the threats.

Automotive

We are already witnessing the introduction of electric vehicles carrying battery storage and alternatives, such as hydrogen fuel cells. New threats may therefore emerge in accident situations. First responders will need to know what storage technology is being used in order to understand the risks and appropriate actions to take. How to react to a charged and damaged battery will differ from a vehicle carrying hydrogen or gasoline. Beyond the first responders*, there are second responders*, who clear away damaged vehicles and must apply the appropriate procedures to ensure their own safety and that of those around them.

Shipping and maritime

These are long established sectors which are safety-focused, hence confidence in the safety of any new technology here is very important.

These industries are already familiar with producing and carrying energy dense cargoes and the risks associated with these are well understood and managed. Before energy storage can be adopted by these industries, the risks (fire, explosion, cryogenics, chemical hazards, etc) need to be understood and managed down to at least a similar level of risk as currently encountered. Furthermore maritime assets are large and complex systems; the addition to, or replacement of, current technologies will impact design, operation, maintenance procedures and skills within the industry.

Safety at sea is of particular importance and new systems must undergo rigorous evaluation to ensure that they do not reduce an asset's ability to maintain function (float, move, contain cargo, communicate, etc). In maintaining function, there is a need to consider the harsh marine environment that energy storage technologies would be exposed to, such as a wide variation of temperatures, motion from waves and corrosive seawater.

* see glossary page 53

Case study 3 – Overhauling ships

The Scandlines ferries form vital links between Scandinavian countries and the European mainland, crossing the Baltic Sea more than 100 times per day. Until recently, these ferries were powered exclusively by diesel engines, but Scandlines transformed them to use lithium polymer batteries for onboard storage. This has involved a stepwise process, with the first hybrid ferries making use of both technologies, aiming for full battery-power on the Puttgarden-Rødby route by 2020. With conventional diesel vessels, both electricity supply and demand varied, with diesel generators supplying a greater or reduced load as required. The remaining diesel generators in the hybrid ferries can run at a constant and optimal load with the battery buffering the variable demand. The weight of the batteries was less than the diesel engines they replaced but a control system needed to be installed to manage the buffering process. This control system needed to be integrated with the main switchboard and control panels.

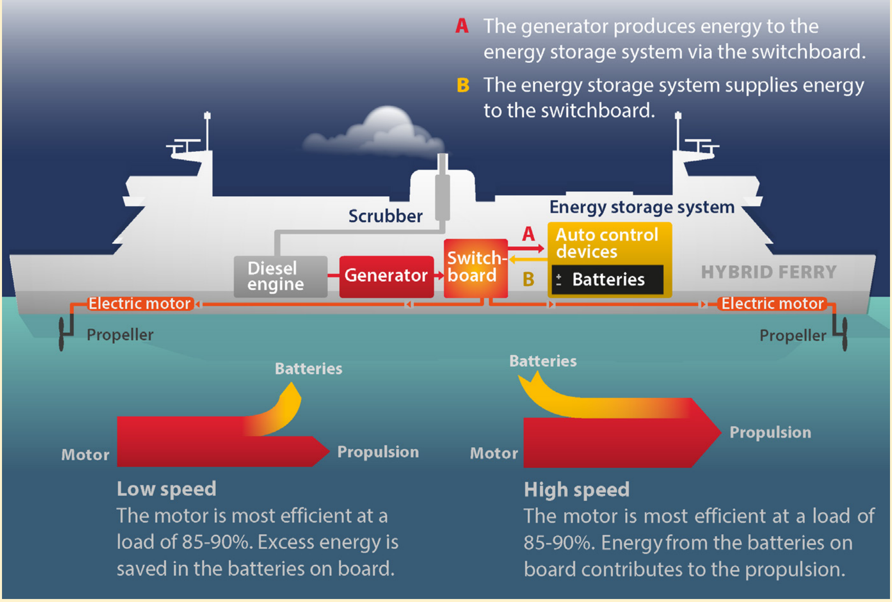
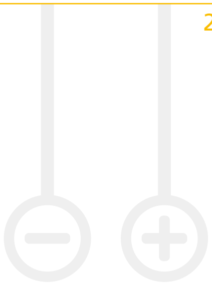


Image courtesy of Scandlines Danmark ApS



Fixed land-based infrastructure

Energy storage products are being added to the energy infrastructure, be this in the development of ‘off-grid’ energy systems independent of any centralised structure, or changes within existing national systems in developed economies. The introduction of such technologies can introduce risks to safety at different scales. At the individual scale, batteries are being deployed at the level of individual households (for example, to support rooftop solar panels). At the town or city scale, deployment is close to greatest energy demand (hospitals, schools, shopping centres or communities). Large scale energy storage could be located close to renewable generators, providing power when conditions do not produce energy for short periods or between seasons. While there are advantages to having smaller concentrations of dispersed energy storage in a distributed energy model, these may be in direct contact with people. Grid scale storage installations could be placed far from human habitation and any hazards, while occurring at a larger scale, could be contained.

Some specific examples of how energy storage could impact on safety are listed below.

- There could be millions of generation and storage devices connected to the network, such that highly distributed and complex control systems will be needed to balance supply across a range of scales.
- Highly distributed energy storage systems may be more complex to start up if the system goes down.
- Many different storage options and chemistries complicate standardisation.
- For first and second responders, it will become more difficult to know what system is in use and what hazards must be managed. For example, it may be difficult for the fire service to know how to deal with one battery fire compared to another, or understand if hydrogen, cryogenic or corrosive chemicals could be leaking. This is made even more complex if different technologies and/or chemistries are co-located on the same site.
- Energy storage systems are capable of providing a range of different services to the network. Which of these takes priority during times of system stress is just one of the control challenges which will need to be addressed.
- Complex connected networks can be at risk from intentional or unintentional disruption that risk resilience of the system.
- In a rapidly emerging area, incorrect technology investment choices can be made, resulting in wasted or stranded assets that require decommissioning.

Case study 4 - A matter of scale

Storage can be installed at different scales to provide different services. For grid support, a large scale storage facility can restore flexibility to electricity grids which are increasingly integrating inflexible renewable energy, allowing system operators to balance supply with demand. Behind-the-meter* storage is an attractive option for people who already own clean energy generation assets, such as rooftop solar panels, allowing them to make the best use of these assets and potentially opening up new revenue streams. If these assets remain connected to the national grid, there is the option for them to work together to provide the same function as a large-scale facility.

Utility scale storage

The Huntorf compressed air energy storage (CAES) plant opened in 1978 in Niedersachsen, 30 km northwest of the city of Bremen, West Germany. It was the first large-scale commercialised CAES plant in the world and was initially built to provide power needed by local nuclear plants to start up and to mitigate peak prices. Its ability to respond faster than coal-fired plants was particularly valued.

The plant employs two cylindrical underground caverns at depths between 650 and 800 metres within the nearby coastal salt deposits. These caverns store off-peak energy as compressed air, reaching pressures of up to 70 bar. The facility can generate up to 290 MW of power for two hours, releasing it into the transmission network when demand is high.

The Huntorf CAES plant is now also used to buffer intermittent wind power generated in northern Germany, enabling system operators to manage the grid in a cost-effective manner. In the event of a blackout, the plant can operate independently to ensure that power is available for critical infrastructure and services.

The plant has operated reliably and consistently over the last 40 years, being available 90% of the time and showing a 99% reliability. Its round-trip efficiency is low, only 42%, but if it had been built today, implementing modern advances in this technology, it could reach 80%.

* see glossary page 53

Household solar hot water tanks

Water is a convenient medium for storing heat, because it can store more heat by volume than many other substances. Many homes in the UK and US still have electrically heated water tanks which can be powered by solar energy and by excess grid electricity. The hot water can be used directly or for space heating. PowerShift Atlantic is a Canadian project spanning New Brunswick, Nova Scotia and Prince Edward, aiming to control a combined 26 MW of a variety of connected loads, including thousands of water heaters in homes. The water heaters need to be able to communicate with and receive signals from the grid, in order to participate in this grid balancing scheme.

The primary advantage of this behind-the-meter storage is its ability to allow the homeowner to optimise the use of their renewable energy assets, allowing them to store the energy absorbed during the day and use it in the evening. This distributed home storage can play a role in supporting the grid in developed nations. In countries which do not have a reliable grid, home storage has an even greater role to play in enabling 24-hour access to services; for example, air conditioning, which is expected to be more widely needed as our world warms further.

Supply chain and environmental impact

The supply chain of a product incorporates all the materials and components involved in its construction, distribution and use, extending to second and/or third life and decommissioning. Potential negative impacts are summarised in the following.

- Some of the raw materials are rare; others can become rare due to increased demand.
- The extraction, production and distribution of raw materials used to construct the energy store can threaten the environment and safety of workers or people living near to such locations. For example, cobalt mining has recently been criticised for unethical and unsustainable practises (Frankel, 2016).
- It can take significant amounts of energy to produce storage devices, hence determining the embodied energy* will be important to support whole lifecycle assessment* studies.
- There may also be safety issues associated with the movement and delivery of energy storage products, for example the movement of certain types of batteries by air freight, which requires the battery to be fully discharged before transport. We are already seeing some types of consumer devices banned on aircraft over fire risk concerns over the batteries used. The degradation of certain battery chemistries is enhanced by fully discharging them, impacting their later usability.
- Recycling at end of life will also become increasingly important, as is already widely done for lead acid batteries, for example. While recycling of Li-ion batteries is technically possible, it is currently not cost effective, when compared to the cost of using new materials.
- In the absence of recycling, appropriate safe disposal of storage devices will be important to avoid contamination of soils or water supplies, fires or explosions.

Device level threats

Incorrect design or failure of the energy storage device itself during operation could result in threats to safety of individuals, property and the functions supported by the device. A summary of the range of potential issues is given in the following.

- Large water reservoirs for pumped hydro represent a potential risk of flooding if water cannot be contained or drained in a controlled way.
- Increased energy density is desired to reduce weight, volume and cost, but concentrated energy stores may be more hazardous in themselves.
- Fires and explosions, associated with an uncontrolled and rapid release of stored energy, are clearly a safety concern.

* see glossary page 53

- Batteries, in particular, can contain flammable materials which release heat and vapours on ignition.
- The energy store can contain both toxic and corrosive materials.
- Heat/cold storage can generate extremes of temperature.
- Hydrogen is a flammable gas with a wide explosive limit.
- The long-term geological hazards associated with underground storage of compressed air or hydrogen need to be established, in particular over multiple charge/discharge cycles.
- Operation of an energy store outside the manufacturer's recommended conditions is likely to occur in the real world.
- Once operating under real world conditions additional threats to safety arise from a range of issues, such as theft (especially if the store contains expensive materials), vandalism, terrorism and cyber attacks.

Large water reservoirs for pumped hydro represent a potential risk.

How do we mitigate the threats to safety?

It is evident from the previous chapters that, while energy storage can bring multiple safety benefits, it also has the potential to negatively impact safety. The actions which can be taken to manage these threats in order to gain the maximum benefit from this technology, are discussed in the following sections.

Public engagement

Public engagement is considered to be an important topic in the context of energy storage. The public is comfortable with the concept of using batteries to store energy, as people are familiar with the technology from consumer devices. By contrast, the use of hydrogen to store and carry energy may be viewed with concern because of its association with the ‘hydrogen bomb’ - a consequence clearly not supported by many years of safe industrial use. Both issues reflect a lack of public understanding: the first may reflect over confidence, while the other demonstrates undue concern. A balanced, high visibility public engagement programme is needed for the public to understand the true value to society of energy storage, actual and relative risks, and comparisons with current solutions. This is particularly important at times following accidents, when the media can project negative information out of context.

Skills and knowledge

In order to support the uptake of energy storage systems there is an urgent need to develop individuals with the correct skills and knowledge to be able to design, operate, maintain, manage and respond to energy storage and the systems within which they reside. Such individuals will require a broad skillset including topics such as hydrogen, natural gas, thermal, mechanical, electrical systems, whole systems, maintenance, disposal and emergency planning. The competency of these individuals should be demonstrated and accredited.

A better understanding of how energy storage systems degrade and fail is needed, from researchers to the general public, in order to design safer, more reliable systems, and also to operate systems in a way that preserves their function and safety.

Training of first and second responders will be essential, as different technologies pose different hazards. They will need to understand the risks of exposure to materials or temperatures contained within the energy store, as well as the fire and explosion hazards that could result from failure. Training of those involved in clean-up after an incident will also be needed, so that suitable handling procedures are established.

Standards, assurances and certification

Standards, if properly implemented by being practical, affordable and appropriate for the use case, are an important tool for assuring safety. Few standards exist for the emerging range of energy storage technologies and these tend to be bespoke for a particular technology option. Universally accepted energy storage standards and codes of best practice are needed along with assurance and certification schemes to support them. Energy storage technologies always form part of a larger system and it is important that the interoperability between systems, responsibility and accountability be clearly addressed. Understanding the role of standards and certification in this context is important, especially for hybrid systems where different storage technologies may be used together and hence interactions will occur.

The adoption of construction design and management (CDM) philosophy to ensure intrinsically safe design should be encouraged. Designs should optimise manufacture, maintenance and recycling. Where storage systems may be re-used, re-purposed, or decommissioned, the design process should consider how safety will be maintained. This may include monitoring devices throughout life and sharing this information throughout the supply chain, perhaps needing a secure and independent third party to hold the data.

Infrastructure

The method of integration and the choice of location for storage into the energy system as a whole will impact safety. For example, the impact on system reliability of a highly distributed/off grid versus more centralised system is not yet fully known. The link between the design of the energy system and the lifetime of energy storage devices is as yet unclear. The duty cycles* imposed on these devices will impact their lifetime and failure risk. For example, charging and discharging more quickly is likely to reduce the lifetime of many battery technologies, but this is generally not taken into account when considering the design of future energy systems. An integrated approach will be needed across all energy vectors, including electricity and gas (natural gas in the near term, moving potentially to hydrogen or synthetic gas in the medium to long term) to properly understand the opportunities to improve safety associated with energy storage.

Where possible, automated monitoring and failure prediction models should be incorporated, allowing systems to identify imminent failure and implement appropriate mechanisms to avert it. The design of the system will have to take into account even unpredictable events, by incorporating resilience through redundancy and failsafe

The system will have to take into account even unpredictable events by incorporating resilience through redundancy and failsafe mechanisms.

* see glossary page 53

mechanisms, especially around critical services. Knowledge of the local geography and population needs and priorities would allow an energy system to respond in accordance with local requirements. The accuracy of prediction software is constrained by the accuracy of the data it has access to, therefore a database detailing the probabilities of failure under specific conditions and their likely consequences would be of great value. This data would need to be carefully curated and frequently reviewed by experts.

Supply chain and environmental impact

A range of measures can be embedded in the supply chain to enhance safety and reduce environmental impact. Where energy storage devices are made with rare or limited materials, or materials which are dangerous to extract or toxic, it should be possible to find alternative materials that are safer and widely available. Accreditation of energy storage systems could incorporate safety and green credentials and lifecycle assessment.

Extending the life of devices makes energy storage more sustainable. This process should start with design that is informed by knowledge sharing and learning from failures, manufacture with materials and components that are assured to relevant standards, and independent testing to have a consistent benchmark for long-term performance. The ability to assess the condition of a storage device will allow devices to operate for longer if in a good condition or if appropriate maintenance is conducted and warranties maintained. The development of technologies that can extend life or rejuvenate the devices would also be of great benefit.

Decommissioning of devices refers to their end of life including recycling. Recycling should be an integral part of design as already mentioned, however, it is important that the devices end their lives at a location where they can be recycled. Ownership of the devices by the supplier, in a similar model to aero engines, where they are leased from the supplier and the supplier is responsible for decommissioning, could drive an increase in life extension and safe recycling for some types of storage.

Device level threats

The recent safety issues with the Samsung Galaxy Note 7 show the risks that can be associated with poor device design or manufacturing quality, in the pursuit for ever greater performance. Indeed, confidence in this emerging technology could be lost if there are incidents such as household fires resulting from the use of energy storage at the domestic scale. Therefore, safe operation must be ensured, not only to protect life and property, but also to safeguard the future use of the technology.

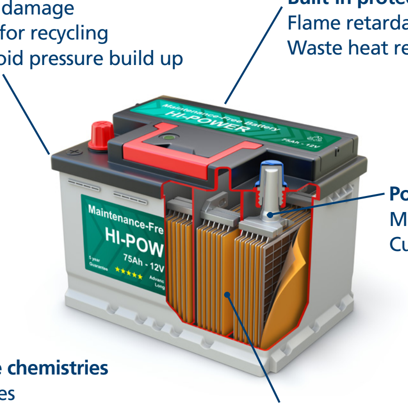
Hence, it is essential that appropriate care is taken to engineer intrinsically safe devices and to properly test these under a wide range of real world conditions. This enables the development of a broad understanding of the failure modes and how these are influenced by local environmental conditions, for example, temperature and humidity, as well as the manner in which the devices are used and controlled. There are a number of points to consider when seeking to improve safety at the device level through materials selection, device design and manufacturing.

- Reverse engineering safety is often expensive and less effective. Designing devices and systems with safety in mind from the start should be encouraged.
- The development of intrinsically safer storage technologies should be encouraged. For example, the development of solid state batteries which avoid flammable electrolytes, or the use of safer chemistries, such as aqueous batteries.
- Measuring the states of charge health of energy stores and how this evolves over time in service is important and is currently difficult for many energy storage technologies.
- A full understanding of all the materials used within the device, and how these may interact or respond to unanticipated conditions, is important. For example, an accident may cause a runaway thermal* reaction leading to rapid heat generation and risk of fire.
- An understanding of manufacturing quality is important, including an analysis of the distribution of flaws within the device and the impact of these flaws on failure.
- The ability to predict and simulate the impact of real world usage of, and accidental damage to, devices and systems may enable designers to build in greater tolerance, or authorities to develop suitable emergency measures.
- Use of power electronics* within the device could bring additional control, enhancing safety.
- Device design should ensure that repair and maintenance can be readily carried out.
- Adequate shielding to protect against leaks, fires, extreme temperatures and explosions would mitigate many of the hazards, however these additional features need to be designed in such a way that they still allow access by authorised personnel for maintenance, repairs and disposal.
- Appropriate fail safe mechanisms and control measures are needed to make installations robust to theft, vandalism and cyber attacks.
- The hazards of large water reservoirs are well understood through years of experience with dams. However, for each location, specific emergency measures need to be put in place and regular inspections of the reservoir containment walls and emergency water relief channels must be carried out.

* see glossary page 53

Case study 5 - Inherent safety and recyclability through better design

Improper disposal of batteries can result in heavy metal pollution of nearby communities. For example, in Haina in the Dominican Republic in 1997, it was found that 91% of a study of 146 children suffered from lead poisoning, largely attributed to toxic fumes emitted by lead-acid batteries in an abandoned recycling plant. During their operation, batteries can cause hazards too. For instance, in 2013, three Tesla Model S electric cars caught fire after their Li-ion batteries were damaged in collisions.



Better packaging
Self-sealing to keep oxygen out
Prevent structural damage
Easy to dismantle for recycling
Safety vents to avoid pressure build up

Built-in protection
Flame retardants to prevent fire or explosion
Waste heat recovery for thermal power

Power electronics
Monitor cell age and temperature
Cut off current to faulty cells

Safer, less reactive chemistries
Solid-state batteries
Lithium–sulfur (Li-S) batteries
Aqueous batteries

Safer structure
Large numbers of low power cells
Improved separation to avoid short circuits
Built-in sensors to detect chemical or gas leaks

Realising the opportunities for improved safety

Four key opportunities that address how energy storage can enhance safety have been identified: the sections below discuss what is required to fully realise these opportunities.

Four key opportunities were identified earlier in the review that addressed how energy storage can enhance safety: enabling mobility; use of heat and cold; power resilience; the environment and sustainability.

For developed countries, existing energy infrastructures can be transformed into low-carbon, efficient and smart systems in a cost-effective manner, integrating both distributed and centralised renewables with storage in a top-down approach. For developing nations, costly development of a national energy system can be bypassed, allowing remote communities access to continuous energy and all the benefits this brings. Furthermore, increased use of sensors and unmanned autonomous devices for inspection and monitoring can be enabled.

The sections below discuss what is required to fully realise these opportunities.

Understand and promote the value and benefits

The uptake of energy storage technology will be driven either by demand from end users, by policy which promotes its use, or at the least does not favour one technology over another, or by cost. For each of these drivers, there is a need for wider engagement to provide the information that is needed for appropriate decisions to be made.

The wider benefits of energy storage and its role in energy systems, including enhancing safety, can best be expressed through the development of specific use cases, for example showing how storage can benefit remote communities on islands (see case study 1 on page 11) or minimising food waste by ensuring food is kept at consistently low temperatures throughout the delivery chain (see case study 2 on page 23).

A deployment plan which identifies and prioritises key services to be supported or developed through energy storage would be helpful in directing attention to where it is most needed. The success of such deployments will also serve to demonstrate the value of storage integrated into energy systems.

Research needs

The research needs for grid scale energy storage technologies in the UK have been recently summarised in the white paper, UK Research Needs for Grid-scale Storage Technologies (Brandon, 2016). This addresses the technical research requirements of a range of energy storage devices, namely lithium and sodium ion batteries, flow batteries, aqueous batteries, supercapacitors, compressed air, heat/cold, hydrogen and storage integration. Similarly, the Automotive Council UK has produced a roadmap listing the research outlook for energy storage in transport applications (Automotive Council UK, 2013). Although these are UK reports the findings are considered global. Additional research needs are identified below.

- New forms of liquid storage, such as solar fuels*, need to be explored, providing a low carbon, easily transportable and long-term energy storage medium.
- Inter-seasonal storage needs to be addressed. In cold countries, this would focus on storing heat for the winter months; in hot countries, the focus would be on cold stores for air conditioning.
- Safety requirements for operating energy storage in extreme conditions need to be considered.
- Safer, cheaper and more abundant raw materials need to be explored.
- Cost reductions will always help to increase the uptake of a new technology, however other benefits such as reduced footprint in terms of size and weight, efficiency improvements or longer lifetimes can help to offset costs or enhance their desirability, in comparison with alternatives.
- Full lifecycle assessments of the costs, embodied energy (total energy for product life-cycle including raw material extraction, transport, manufacture, assembly, installation, disassembly and deconstruction), and environmental impact of each technology are needed to select the best technology for long-term, sustainable deployment. Full and fair comparison of the risks presented by energy storage with those inherent in incumbent technologies, which would be displaced by storage, would help give a balanced view.
- Development of new designs which address the need for safety, ease of maintenance and sustainable disposal of energy storage technologies, along with the impact of these designs on performance and cost.

* see glossary page 53

- Consumer behaviour studies are needed which assess the public understanding of the risks and benefits of energy storage.
- Retrofitting of energy storage to complex systems, for example those on board ships, is likely to introduce new conflicts and greatly increase complexity. In some cases, energy storage may be fitted into existing systems and in others it may prove more efficient and economical to replace the existing system with a new and simpler system, which has integrated energy storage. Therefore, whole system studies are needed that consider both the needs of the applications and the interactions between different energy carriers such as electricity, natural gas, heat and hydrogen. Looking more widely at other systems, such as waste and water treatment and supply, may identify further synergies and allow the benefits of storage of electricity, heat, cold, chemicals and water, both within and between sectors to be assessed.

Infrastructure planning

With the twin threats of climate change and its associated greater temperature extremes, as well as the increasing demand from a growing population, an energy system which can supply sufficient energy in a sustainable manner is essential to safeguard the long-term success of modern societies. There is an urgent need for strategic, holistic energy systems planning, to ensure that the most suitable energy systems are deployed, taking into account not only their cost, but also their long-term benefits. Safety is clearly a vital aspect to consider in the planning and evaluation process.

Development plans for electricity systems should be co-ordinated with other key infrastructures, such as communications, water delivery and treatment systems and the gas grid, as well as the wider mobility and heating networks. We are currently presented with a unique but relatively narrow window of opportunity to transform existing systems or design new ones for long-term benefit.

Whole systems modelling, incorporating multi-dimensional data on technologies and their failure mechanisms, user behaviour, system operation modes, as well as weather and sunshine forecasts, enables insights into possible routes for achieving optimal cost and/or lowest carbon emissions. Targets and milestones defined in technology roadmaps can help us to determine if the expected routes are being achieved.

When choosing technologies to deploy, the needs of the beneficiary community should be the primary consideration. For example, in regions which primarily require heat, the deployment of thermal technologies or hydrogen is implicated. In areas where there is a high demand for low voltage applications, such as lighting and electronics, networks transmitting a reduced voltage avoid the need for wasteful transformers.

An energy system which can supply sufficient energy in a sustainable manner is essential to safeguard the long-term success of modern societies.

An energy system which makes use of waste products from other sectors and minimises or reuses its own waste would be of great value to society by ensuring sustainability and avoiding the build-up of debris and toxic materials. Waste products from industrial and agricultural processes should be identified and considered as possible feedstock for energy systems. Many processes produce waste energy in the form of heat or cooling, providing an integration opportunity for thermal energy storage technologies.

Because the opportunities and resources available to developed nations are slightly different from those for developing nations, the actions required to support and encourage the deployment of storage differs. For nations with established power grids, the flexibility that storage can provide is its greatest benefit. Opportunities for integrating storage with existing systems, including electricity, water and gas infrastructures, as well as fuelling and transport networks, will need to be identified and exploited. Efficiency and capacity issues will tend to dominate in areas which already have access to power. By contrast, developing nations may not have a well-developed infrastructure and solutions which address local needs and resources will be more successful. For example, energy storage can be part of a larger solution providing medical care or education for communities which lack these amenities.

Case study 6 - With or without a grid

Nationwide grids were developed at a time when the long-term effects of fossil fuel use were largely unknown. Their designs reflect the inherent flexibility of fossil fuels, allowing generators to be turned on and off as demand requires. With the current transition towards intermittent renewable energies, the grid needs this flexibility to be replaced by technologies such as storage, demand side response (where electrical devices such as fridges and washing machines can be scheduled to run during periods of low demand or excess supply so helping the grid to maintain power balance), and interconnectors (which link to the grids of neighbouring countries, allowing all countries involved to balance each other). In countries which have established grids, installations of large, centralised storage assets are likely.

Behind-the-meter storage is an attractive asset for people who already own clean energy generation tools, such as rooftop solar panels. In developed countries, this may one day surpass centralised storage, but where distributed storage currently offers the most benefits are in developing communities which have no or poor access to a nationwide grid. For these, the solution is a bottom-up approach, where generators and storage are integrated into a new grid.

Microgrids in Kenya

While poor electrical infrastructure means that the scattered, remote populations of many African countries do not have access to power and the benefits this brings, there is the advantage of being able to develop a new energy system from the bottom up, without the need to transition from an established system.

PowerGen Renewable Energy is one of many companies operating in East Africa to develop microgrids to power homes and businesses at low cost. PowerGen's mission is to 'transform lives through smart power'. Microgrids are local smart grids containing all the essential features of a traditional grid, enabling them to run independently. They can potentially be connected up to form a larger energy network at a later stage.

The majority of the 1.2 billion people in sub-Saharan Africa currently rely on polluting diesel and other fossil fuels to power their devices, however sustainable energy sources such as wind and sun are abundant. PowerGen offer an environmentally sound alternative which is relatively cheap and simple to install and maintain, based largely on solar panels, batteries, fuel cells and smart meters. The local community uses these

'PowerBoxes' to run small businesses, from restaurants to hair salons, as well as vital community services such as clinics and schools. The autonomy that these facilities offer makes them particularly appealing in remote locations, while retaining the option to connect to national grids at a later stage. To date, PowerGen has connected more than 1,800 customers through over 40 solar mini-grid installations across East Africa.

This approach provides a cost-effective and low carbon way for African countries to provide energy and critical services to remote communities, tackling fuel poverty and improving the quality of life for all, enabling the growth of local economies and connecting people to online information and services.

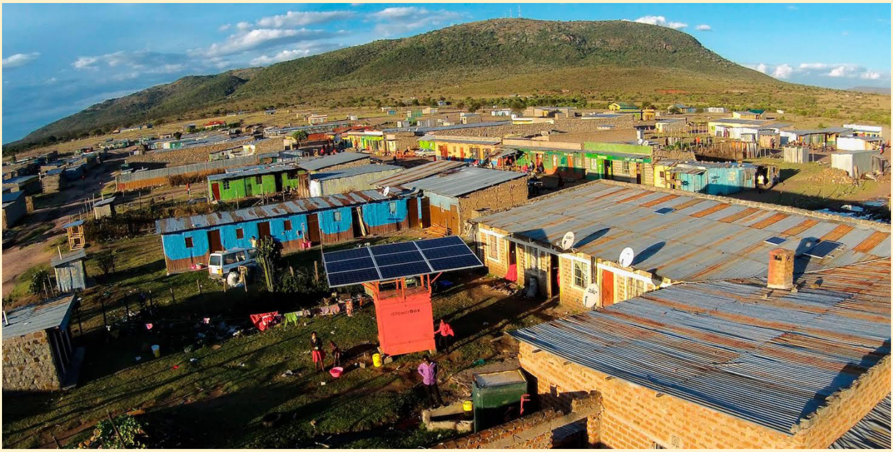


Image courtesy of PowerGen Renewable Energy

Demonstrators to improve learning and confidence

Energy storage can offer more than just balancing supply with demand and the range of benefits can best be explored and demonstrated to industry and the public through transport and off-grid prototypes developed for specific applications. These demonstration projects would also allow the safety and operational aspects of energy systems to be tested with integrated storage, and could serve as educational tools for training engineers, technicians and a range of other operators, including the public.

The following list of projects would demonstrate a range of key aspects.

- Grid-scale demonstrators of various energy storage technologies, both to support networks, and to provide backup power for critical systems such as data centres. Many of these are already installed in developed nations with well-established power systems, such as the 6 MW/10 MWh battery being trialled by UK Power Networks at Leighton Buzzard and the MYRTE project in Corsica, which is assessing the feasibility of storing solar power as hydrogen. These are useful for exploring system-level issues, such as business models and operating paradigms.
- Case studies which transform entire cities into smart grid testbeds. Since future populations are expected to be concentrated in cosmopolitan areas, these case studies would demonstrate new integrated system concepts at an appropriate scale, incorporating city-wide infrastructures for water, energy and transport. An example is Zhangjiakou, a Renewable Energy Demonstration City in China which aims to be 100% powered using renewables by 2022.
- New cities or towns are an ideal opportunity to develop new integrated infrastructures, including electric vehicles and their integration into energy systems, drawing on lessons learned from other pilot projects and optimising infrastructure through coordinated planning. The UK is leading the new town movement and examples are North West Bicester and Rackheath Eco-town.
- In areas which have no or limited access to a power grid, new microgrid energy systems can be developed with integrated storage. This provides a good testbed for exploring new system architectures, without the constraints of having to conform to legacy rules or interface with established systems. This is already occurring in many island nations (see case study 1 on page 11).
- In developing nations, the opportunities for developing the local community could be clearly demonstrated through easily deployable examples. For instance, several companies have developed containerised modules for rapidly deploying in clinics, schools, farms, etc.
- Shipping and offshore demonstrators will show that low carbon energy storage in a highly regulated sector is feasible. The demonstrators can also inform future design of both the systems and their associated assurance and regulatory mechanisms.
- It is easier to integrate storage into new buildings but a large proportion of buildings are already established and the challenge for new energy systems would be to successfully demonstrate how existing buildings, from residential to commercial, could be retrofitted. This would provide opportunities to test and amend the regulatory barriers, particularly for listed buildings protected by various policies and laws. The suggestion was made for the Lloyd's Register Foundation's 1900 building in London to be considered for retrofitting energy storage, as a showcase.

Zhangjiakou, a Renewable Energy Demonstration City in China
Image credit: Wangyunfeng (Own work)
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In order to maximise the learning from these projects, all relevant data must be collected and made accessible to anyone wishing to learn from the experience gained. Existing demonstration projects are already developing mechanisms to share knowledge and data. There would be great value in having this data centrally managed and co-ordinated, to ensure that the data is always available, securely stored and well structured, so that it can be easily understood and mined. Failures, in particular, should be carefully recorded to highlight areas requiring improvement. The data should include all environmental conditions during operation, device makes and models, duty cycles and performance at all levels, from device components to systems. In addition, users of the system should be given the opportunity to comment on the ease of use and performance of any aspect of the system.

Policy and regulations

Government policies can go a long way towards supporting and encouraging the safe uptake of new technologies. However, inconsistent policies and frequent changes to policy can be very disruptive as they damage investor confidence and cause confusion.
It is important to keep working with governments to ensure that they are well informed of the benefits of new technologies and the need for implementing consistent policies which demonstrate a commitment for clean technologies, low consumption strategies and safe engineering for maximum social benefit.

Targets and incentives which specify a percentage of uptake by a particular date are good drivers for innovation and implementation of new technologies. Policies and targets for developed nations are likely to differ from those for developing nations, as the available resources, local requirements and constraints are different and often location-specific.

An important first step would be the establishment of a new licensing class for storage that adequately recognises all the value it offers. Policies should particularly favour technologies which enhance safety and support the principles of long-term sustainability.

A number of more specific changes to regulation were suggested at the workshop.

- Regulations surrounding the injection of gaseous fuels into the gas grid need to be reviewed to allow cleaner fuels, such as hydrogen, to be used and incentivised.
- The built environment represents a large proportion of energy use and regulations around both new builds and retrofitting for established buildings need to be developed and revised. New developments should integrate renewable generation and energy storage into building materials. Regulatory barriers to installing storage in existing buildings need to be identified and sensibly updated.
- Regulations covering the recycling of end-of-life storage technologies need to be developed, to ensure that responsibility is clearly defined and cannot be avoided. This is of particular relevance to second life/repurposed products, which may be used in countries lacking such regulations.
- Policies governing the repurposing of energy storage technologies should mandate the monitoring of performance throughout the lifetime of use of the device so that, when it is handed over for second life use, a clear record is available enabling the user to fully understand its state of health and limitations for use. This data should be held by an independent authority, to ensure its integrity.
- While standards are useful tools for enhancing the safe deployment of a new technology, without regulations to enforce adherence to these standards, there is no assurance that they will be correctly implemented. Regulations need to be developed to ensure that standards are both accepted and followed at an international level and that education on the use of these standards is available to all users of the storage technologies and systems.

Findings and recommendations

The findings of this review have significant cross-over with previous foresight reviews that have been published by the Foundation. For example, in the Foresight review of structural integrity and systems performance, one of the recommendations is the following: 'The Foundation should support the development of innovative new approaches to whole systems safety in critical infrastructure sectors'. In the Foresight review of resilience engineering, the first recommendation is: 'The Foundation can bring a substantial societal benefit by building resilience in critical infrastructures'.

Drawing from the contents of this review, this section highlights some priority areas in energy storage where progress is required.

Recommendations			
Critical systems support	Through-life safety and sustainability	Public engagement, skills and knowledge	Maximising value from demonstrators
Emergency preparedness	Safety by design	Public understanding of risk	Open data culture
System resilience	Supply chain resilience	Skills development	Test hybrid systems
Integration	Regulations and standards		
	Manufacturer responsibility		

Critical systems support

Energy storage systems will play an increasing role in our daily lives; from the devices in our hands to supporting the critical systems that we rely upon under normal and crisis conditions. In order to gain full advantage from energy storage solutions there is a need to address the following.

Emergency preparedness

As energy storage applications become more common, they will increasingly become a consideration as a part of emergency response. From designers of installations in which energy storage systems will be present, to those that respond to emergencies (such as first and second responders, security staff and medical personnel), there is a need to understand the hazards and emergency measures associated with the different technologies they will come across. One possible area to focus on is the development of consistently clear and standardised signs to indicate the energy storage technology present and associated hazards.

System resilience

If the function of a critical infrastructure system relies on stored energy in some way it then follows that the energy storage device itself must be dependable. In order for the energy storage system to remain functional it must withstand deliberate and accidental conditions that could cause it to fail. For example, storage devices may need to be designed against vandalism, cyber attacks or natural disasters.

Integration

Safe and successful application of energy storage, particularly in sectors which have traditionally relied on energy generated from hydrocarbons, requires an in depth understanding of the specific needs, risks and operations. An example of particular sector singled out in this review is shipping and offshore platforms. Another example is the retrofit of buildings protected by complex legislation.

Through-life safety and sustainability

Decisions taken at the research and design stages of energy storage technologies, devices and systems can significantly impact all aspects of system life. Opportunities exist to improve all stages of the product lifecycle with a particular focus on how safety and sustainability can be enhanced.

Safety by design

A practical understanding of how devices will be made, how they will be used, and how they will decommissioned together with the problems associated with each of these, can lead to designs that are safer to build, use, maintain, refurbish and recycle. Such studies should also address the impact of these designs on the financial and environmental costs and performance of devices.

Supply chain resilience

The supply chain of a product, from raw materials extraction to decommissioning, has opportunities to improve the safety of people involved, the quality of the product, and the sustainability of the product. Research into lifecycle assessment and management, independent benchmarking, and promotion of a shared learning culture between manufacturers and commercial operators, would support this. This approach would offer long term benefits and identify where improvement is needed.

Regulations and standards

Standards, codes and good practice guides are effective routes to assuring safe design, manufacture, installation, operation, maintenance and decommissioning of energy storage systems. Regulation and certification of new technologies should be considered throughout the research and innovation processes, rather than being considered at the commercialisation stage. Having consistent global approaches that are practical, can be applied across sectors, and can be independently audited, would create conditions that support the uptake of the technology.

Manufacturer responsibility

Secondary markets, often in less advantaged communities, need to be protected from having poorly functioning, faulty or hazardous equipment passed on to them; manufacturers and owners should take full responsibility for decommissioning and recycling.

Public engagement, skills and knowledge

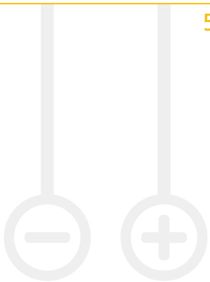
To experience the benefits that energy storage can bring, it needs to be used in the real world. Successful uptake of the technology will depend upon people: people will need to be willing to use the technology and people will be needed to install and maintain the technology.

Public understanding of risk

There is a need for a trusted, independent, international body that can give a balanced view of the risks associated with energy storage technology. The body should be able to understand public concerns and communicate effectively to reassure when concerns exist that are unfounded and also highlight risks when the public do not perceive them. Such a body would need to be highly visible so that it can be heard when misleading articles are reported in the media. This group could draw up full and fair comparisons of the risks presented by a variety of energy storage options, particularly highlighting those already present and accepted in traditional technologies, which would be displaced by cleaner storage technologies.

Skills development

A workforce is needed with relevant skills for installation, maintenance and disposal of energy storage technologies that are used in the local community. Skills development could take the form of certification and accreditation programmes, apprenticeships, self-certification or adult education programmes. The trainers of these programmes would themselves require training and support, as well as accreditation. Repowering London has developed this model to engage and empower the poorest communities in London in the development of more reliable energy systems to supply their needs.



Maximising value from demonstrators

The success and safety of new technologies or systems is often proved by full scale testing in demonstrator projects. Such demonstrator projects can be enhanced by incorporating the above findings. The following additional recommendations would maximise the learning from demonstrators, serving as examples for future installations around the world and establishing best practises for energy management and storage.

Open data culture

The Foundation's Foresight review on big data highlights the need for an open data culture to maximise the learning from key research projects and demonstrators.

Test hybrid systems

In many cases, there is not one energy storage system being used but hybrid systems, that bring together a number of storage technologies working together to enhance overall performance. Existing demonstrator projects, such as those in Barbados and the Orkneys, could be used to understand the complexity of hybrid systems, their capacity to work together, and lead to better future solutions.

Recommendations

These recommendations focus mainly on emergency preparedness and resilience of systems. This is because there is 'white space' where the Foundation can bring additional value into areas that are not currently a focus.

Appendix: Glossary, references and further reading

Glossary

Behind-the-meter storage	Energy storage installed and intended for on-site use in a home, office building or other commercial facility.
Blackstart	The process of restoring an electric power station or a part of an electric grid to operation without relying on the external transmission network.
Cryogenic	Very low temperatures, usually below –150°C.
Degradation	The reduction in performance of devices over time and use.
Duty cycle	The cycle of operation of an intermittent, rather than continuous, device.
Embodied energy	The energy consumed by all of the processes associated with all the stages of a product's life, from raw material extraction to disposal.
Energy demand	The requirement for energy as an input to provide products and/or services.
Energy density	The amount of energy stored in a given system or region of space, per unit volume or mass.
Energy generation	Conversion of an available energy source, such as fuel, sunlight or wind, into a usable form, such as electricity or heat.
Energy vector	A means for transferring a quantity of energy in space and time.
Exothermic	Describes a reaction which releases heat.
First life	The initial service a device provides, directly after manufacture.
First responders	Police, fire and emergency medical personnel.
Heat exchange fluid	Any gas or liquid specifically manufactured for the purpose of transmitting heat from one system to another, for example coolants.
Heat pump	A device that transfers heat from a colder area to a hotter area by using mechanical energy, as in a refrigerator.

Islanding	The ability of a distributed generator to provide power for a location, even when electrical grid power from an electric utility is not present.
Lifecycle assessment (LCA)	(Aka cradle-to-grave analysis) A technique for assessing environmental impacts associated with all stages of a product's life, from raw material extraction to end-of-life disposal.
Lifetime	The length of time for which a device is economically or practically usable, often limited through degradation processes.
Load	An electrical load is an electrical component that consumes electric power.
Low grade or waste heat	Low- and mid- temperature heat below 370°C, which cannot be efficiently converted into a usable form.
Peak shaving	A technique used to reduce electrical power consumption during periods of maximum demand on the power utility.
Power electronics	Electronic circuits which control the flow of electrical energy.
Round-trip efficiency	For storage systems, this is the ratio of energy put in to energy retrieved, expressed as a percentage.
Runaway thermal	An exothermic* reaction, where the heat released increases the reaction.
Second life	The continued use of a discarded vehicle battery for grid balancing services. Many such batteries provide up to 80% of their capacity.
Second responder	A worker supporting first responders by preparing, managing and returning services and cleaning up sites, during and after an event.
Sensible heat	The heat which raises the temperature of a gas or object without changing its phase.
Solar fuels	Chemical compounds formed using solar energy.

* see glossary page 53

Superconductivity	The property of providing no electrical resistance, displayed by some substances at very low temperatures.
Syngas (short for synthesis gas)	A fuel gas mixture consisting primarily of hydrogen, carbon monoxide and very often some carbon dioxide.
Turbine	A machine for producing continuous power in which a bladed wheel or rotor is made to revolve by a fast-moving flow of liquid or gas.
Whole systems analysis	Taking into account the effects from all contributors to and users of a system.

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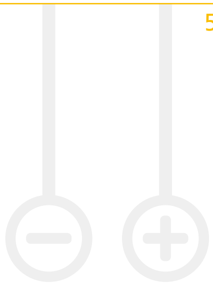

Recommended reports for further reading

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