US-UK scientific forum on sustainable energy

Electrical storage in support of the grid

Held on 17 – 18 March 2021

Forum report

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US-UK scientific forum on Sustainable energy –
Electrical storage in support of the grid
Issued:September 2022 DES7752

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Contents

Message from the Presidents

The effort to meet the ambitious targets of the Paris agreement is challenging many governments. The US and UK governments might have different approaches to achieving the targets, but both will rely heavily on renewable energy sources such as wind and solar to power their economies. However, these sources of power are unpredictable and ways will have to be developed to store renewable energy for hours, days, weeks, seasons, and maybe even years before it is used. As the disruptive and increasingly deadly impacts of climate change are being felt across the world, the need to move to more sustainable sources of energy, and to identify viable ways to store that energy, has never been more important.

This was the subject of the US–UK Science Forum on electrical storage in support of the grid, which was held online from 17 – 18 March 2021. Co-organised by the Royal Society and the National Academy of Sciences, it brought together a diverse group of 60 scientists, policy makers, industry leaders, regulators and other key stakeholders for a wide-ranging discussion on all aspects of energy storage, from the latest research in the field to the current status of deployment. It also considered the current national and international economic and policy contexts in which these developments are taking place.

A number of key points emerged from the discussion. First, it is clear that renewable energy will play an increasingly important role in the US and UK energy systems of the future, and energy storage at a multi-terawatt hour scale has a vital role to play. Of course, this will evolve differently to some extent in both countries and elsewhere, according to the various geographical, technological, economic, political, social and regulatory environments. Second, international collaboration is critical – no single nation will solve this problem alone.

As two of the world's leading scientific nations, largest economies, and per capita CO_2 emitters, with a long track record of collaboration, the US and UK are well placed to play a vital role in addressing this critical challenge.

As the discussion highlighted, a wide range of energy storage technologies are now emerging and becoming increasingly available, many of which have the potential to be critical components of a future net-zero energy system. A crucial next phase is in ensuring that these are technically developed as well as economically and political viable. This will require the support of a wide range of these potential solutions to ensure that their benefits remain widely available, and to avoid costly 'lock-in'. Scientists and science academies have a critical role to play in analysing technology options, their combinations, and their potential roles in future sustainable energy systems, and in working with policymakers to incentivise investment and deployment.

As Presidents of the Royal Society and the National Academy of Sciences, we would like to thank the co-chairs, Chris Llewellyn Smith and Steve Koonin, for leading this important discussion. We would also like to thank the many other Fellows, Members, experts and staff who contributed to organising the event and in writing and reviewing this summary.

As the world's policymakers confront the need for increasingly urgent action in the face of ever-growing threats resulting from higher global temperatures, addressing the challenges and developing the solutions highlighted in this Forum will be critical.

Marcia McNutt

Marcia McNutt
President of the National Academy of Sciences

Sir Adrian Smith
President of the Royal Society

Summary

Multiple factors are driving changes to the UK and US energy systems, including net-zero targets, grid modernisation and the need to replace ageing assets. A high-renewables grid lends promise for a net-zero future as the costs of renewable technologies decreases. Such a grid would need to be backed up by dispatchable sources of power to buffer the mismatch between supply and demand, due to variability in wind and solar resource. Emerging research indicates that periods of wind and solar 'drought' can occur for many days at a time. If the future grid is to meet reliability requirements, dispatchable sources must provide the full power range over multiple days: tens of terawatt-hours of capacity will be required in the UK, and possibly hundreds of terawatt-hours of capacity in the US. A combination of grid-scale energy storage and dispatchable generation (for example combined cycle gas turbines with carbon capture and storage) is likely to be required, determined by the complex interaction of economics, technology development, and regulation. Further flexibility in energy supply can be achieved using interconnectors that link electricity grids across state or country boundaries and by means of cross-sector coupling, whereby energy is transferred between different sectors.

Storage options for dispatchable power was the focus of a two-day joint workshop between the Royal Society and the National Academy of Sciences. The workshop brought together individuals from academia, government, regulators and industry to discuss energy storage technologies, their role in the current and future energy systems, and the economic, regulatory and operational issues affecting their development and adoption in the market.

Energy storage technologies can deliver a whole range of grid services to help maintain a stable and reliable grid, as well as providing dispatchable backup power. In the coming decades, a suite of energy storage solutions over a range of discharge durations – from seconds to days, weeks, months and even years – will be needed for different applications and end-user needs; these include electro-chemical, mechanical/kinetic, thermal and hybrid forms of storage. Batteries dominate current and planned deployment of energy storage, while lower levels of technological maturity have been achieved to date for medium- and long-term storage technologies such as flow batteries, compressed air energy storage and thermal storage.

However, it is anticipated by the US Department of Energy that by 2030 annual stationary storage in the US, excluding pumped hydro, could exceed 300 GWh, representing a 27% annual compound growth rate for grid-related energy storage.

At the current time, grid-scale energy storage technologies are expensive, and only Lithium-ion batteries and pumped hydro are ready for wide-scale deployment without further demonstration and in many cases research. The challenge is to develop and deploy technologies at a sufficient pace to meet net-zero targets – it typically takes a decade to bring technologies of this type from lab to market – and to create a system that is affordable and brings the widest economic, social and environmental benefits. Potential energy storage solutions cover a range of technology-readiness levels, from established technologies to more 'exotic' solutions; it is not yet clear which will emerge as viable contenders.

Materials, chemistry and engineering solutions can be sought to drive improvements in cost, lifetime, power and energy capacity, roundtrip efficiency, sustainability and safety. Furthermore, many technologies are modular and the potential to scale up manufacture to GW scales is present, which is vital for technologies to become competitive. In both the UK and US, current government-funded research programmes address a range of different technologies and focus on lowering costs, increasing performance and scaling up manufacturing capacity. In addition, a number of companies in the UK and US are bringing technologies – from hydrogen electrolysers to solid oxide fuel cells – to market.

Until there is greater clarity about the optimal system, support should continue for a portfolio of plausible energy storage technology options, avoiding pushing individual technologies before their time. A central challenge is the inherent low utilisation of energy storage technologies, and understanding the commercial viability of each technology within the system is important. The development of robust supply chains and limitations in the supply of materials are further issues; solutions that utilise earth-abundant materials are needed. Multiple challenges make technology development and deployment a complex problem, requiring a systems approach.

A use-case perspective is vital; adaptive development will be required as different use cases emerge. Energy system modelling must play an important role in identifying optimal scenarios for the future.

Energy can be stored in green hydrogen and green ammonia. Typically, green hydrogen might be generated using electrolysis during times of excess renewable energy generation and stored underground until it is needed to generate electricity. Green ammonia, produced from hydrogen and nitrogen, has a higher energy density and is easier to store than hydrogen, so could be used to export energy. Both fuels have the potential to enable flexibility through cross-sector coupling. Power could be dispatched when needed from either fuel, using fuel cell technologies. Alternatively hydrogen or ammonia could be used as low- or zero-carbon fuels in GW-scale power plants. Repurposing existing power plants that are already connected to a gas distribution network is attractive, but there are a number of technological and system challenges.

The regulatory and political frameworks under which the energy systems are delivered in the US and UK must be suitable for the transition towards a high-renewables grid with dispatchable backup. While natural gas remains in the system, it is challenging to incentivise the development and deployment of long-duration energy storage solutions. The absence of a market at the current time and uncertainty about the future value of solutions are further obstacles.

There is a risk of failing to produce reliable, least-cost systems to the timescales required by net-zero targets if the market is left to deliver them without intervention from government. Market restructuring is likely to be required over the next three to five years to create appropriate incentives for investment, to develop markets and supply chains that offer a diversity of solutions, and to avoid the market driving the system towards needlessly expensive solutions. It will be essential to continue to deliver reliable energy through any transition.

As the technologies and the system in which they function develop, safety and sustainability will become important considerations. The development of circular supply chains for technologies will help manage both end-of-life considerations and raw material risks. However, environmental factors, including end-of-life costs, are currently not costed into storage solutions such as batteries where this issue is particularly evident; incentives will be needed to promote second life and encourage manufacturers to design for reuse and recycling. Differing safety challenges are present across the various solutions; regulation must take into account public attitudes to risk and public acceptance of the various technologies and their end-uses.

International collaboration can play a vital role in tackling diverse challenges, focused primarily on pre-competitive areas of research. This might include research on both methodologies and technologies, such as energy system modelling; lifetime prediction and performance; methodologies for life cycle assessment; minimising environmental impact; recycling and reuse; low-technology readiness level (TRL) technologies for long-term storage; and potential for repurposing existing power assets.

KEY DEFINITIONS

Energy density – the amount of energy in a given mass (or volume). The higher the energy density, the greater the amount of storage possible for a given mass (or volume).

Power density – the amount of power for a given mass (or volume). The higher the power density, the more quickly energy can be released for a given mass.

Roundtrip efficiency – the fraction of energy put into the storage that can be retrieved when it is discharged.

Lifecycle – number of charge/discharge cycles before the end of life is reached.

Calendar life – expected lifetime of the asset (device or plant)

1. Introduction: the changing energy system

The UK and US energy systems are evolving rapidly. In the UK, electricity generation is currently more than 50% carbon-free, while coal-based generation is being phased out. The UK's renewable energy capacity has grown over the last ten to fifteen years as a result of government subsidies and carbon pricing. In the US, the gas fracking boom has seen coal being rapidly replaced by gas, while wind and solar has developed mainly in 'middle-America' states, partly due to natural resource advantages in those areas. As yet there is no federal carbon price for the US electricity system.

In 2019, the UK set a legally binding target of net-zero emissions of all greenhouse gases by 2050. Two years later, the US administration set a target to achieve a 50–52% reduction in greenhouse gas emissions relative to 2005 levels by 2030 and an aspiration to have an emissions-free grid by 2035. Although moves to decarbonise have varied considerably across states, individual states such as California and New York have already put in place net-zero targets. The timescales for decarbonisation will require an acceleration in the pace of change over the coming decades. Further drivers for change include the need to replace existing infrastructure that is coming to the end of its useful life and the need for grid modernisation as the number of distributed energy sources increases.

It is likely that renewable energy – in particular wind and solar energy – will play a major role in both the UK and US energy systems in future, supported by dispatchable power: either grid-scale energy storage or dispatchable zero-emissions generation such as fission or gas with carbon capture and storage (CCS). These will be required to buffer the mistiming between supply and demand which results from variability in wind and solar resource.

The balance between dispatchable generation and storage will play out in each country over the next decades, determined by the complex interaction of economics, technology development, and regulation. This workshop was focused on the storage options for dispatchable power.

Far more energy is currently stored in fossil fuels than in other forms, such as pumped hydro. As fossil fuels are phased out, tens of terawatt-hours of new storage capacity will be required in the UK, and possibly hundreds of terawatt-hours in the US. A range of technical solutions exists, at varying levels of readiness, and each with their own economic and operational challenges. The development of commercially viable energy storage solutions, with attributes that meet grid requirements, will be vital over the coming decade. Achieving the optimal decarbonised energy system, within the timescales to meet net-zero targets, is a central objective.

This joint Royal Society-National Academy of Sciences meeting brought together individuals from academia, government, regulators and industry to paint the landscape of energy storage, including current research, demonstration, manufacturing and deployment activities as well as current policy, regulatory and market contexts. The discussions explored scientific, technological, operational and economic issues, and identified opportunities for international collaboration. Implications for policymaking were also explored.

2. Designing and operating a high-renewables grid: systems-level issues

System design for reliability

Operating a reliable grid with minimum disruption to supply is a regulatory requirement in both the US and UK. The future high-renewables grid must continue to meet this requirement. Analysis carried out recently in the US and UK, using decades of real weather data, show periods when there is no wind or sunshine for days at a time[1]. System design will be dictated by these weather extremes if the grid is to meet its reliability requirement. In the same way that other types of engineered asset are designed to withstand, say, once-in-forty-year floods or hurricanes, the electricity system must also be designed with wind and solar 'droughts' in mind, using sufficient data to cover historic weather periodicities. Approaches to sustaining critical loads will also be needed. Utility companies and regulators will need to embrace these data-driven approaches. One question is the extent to which past weather data provides a robust design basis for the future system; the degree to which climate change will impact future weather patterns is uncertain.

For high-renewable grids, reliability can only be achieved by providing complementary supply of power that is flexible and can be dispatched rapidly in response to market needs. The (non-exclusive) options are multi-TWh energy storage capacity that is capable of providing energy over many days, or low-carbon dispatchable generation, such as natural gas with carbon capture and storage or flexibly operated (small-scale) nuclear power.

Some degree of flexibility can also be achieved by means of interconnectors, which connect the electricity systems of neighbouring countries or states and enable the trade of electricity across borders. In the US, the opportunity to build additional interconnectors between states offers the potential to reduce the costs of zero-carbon electricity[2]. Cross-sectoral coupling, whereby energy is transferred between different sectors, is a further possibility for the future. Fuels or storage may be available in other sectors, so the mistiming of supply in relation to demand becomes less critical for the energy sector. For example, ammonia or hydrogen potentially have multiple uses in different sectors, in addition to their use in the energy sector, and could be transported to wherever they are needed.

The use of battery electric vehicles as a form of energy storage for the grid is an example of coupling between the stationary and transport energy services sectors.

Given the capital-intensive nature these systems and the potential low utilisation, commercial viability will be challenging. Furthermore, recent UK and US modelling based on real weather data demonstrates that the need for dispatchable power is perhaps one hundred times greater than economic studies have shown, with significant cost implications. This is because dispatchable power would potentially need to provide the full power range to cover periods of wind and solar drought over many days. For example, UK modelling has indicated a shortfall of about 20% capacity for a 600 TWh future UK electricity system. Ensuring the costs of energy storage technologies are affordable, while optimising other aspects of their performance, are central challenges; otherwise, there is a risk that electricity becomes much more expensive in the future.

Towards an optimal energy system

In the coming decades, a suite of energy storage solutions over a range of discharge durations will be needed for different applications and end-user needs. Context is critical in determining what energy storage solution is appropriate – there is no 'one-size-fits-all' solution. Instead, distinct technological and economic niches are likely to emerge as a result of the natural modes of weather variability. Research and development over the coming decade must focus on driving down the costs of energy storage technologies and improving their performance to meet end-user requirements and minimise environmental impact, as well as achieving acceptable levels of safety. Issues around sustainability and safety are discussed further in Chapter 5.

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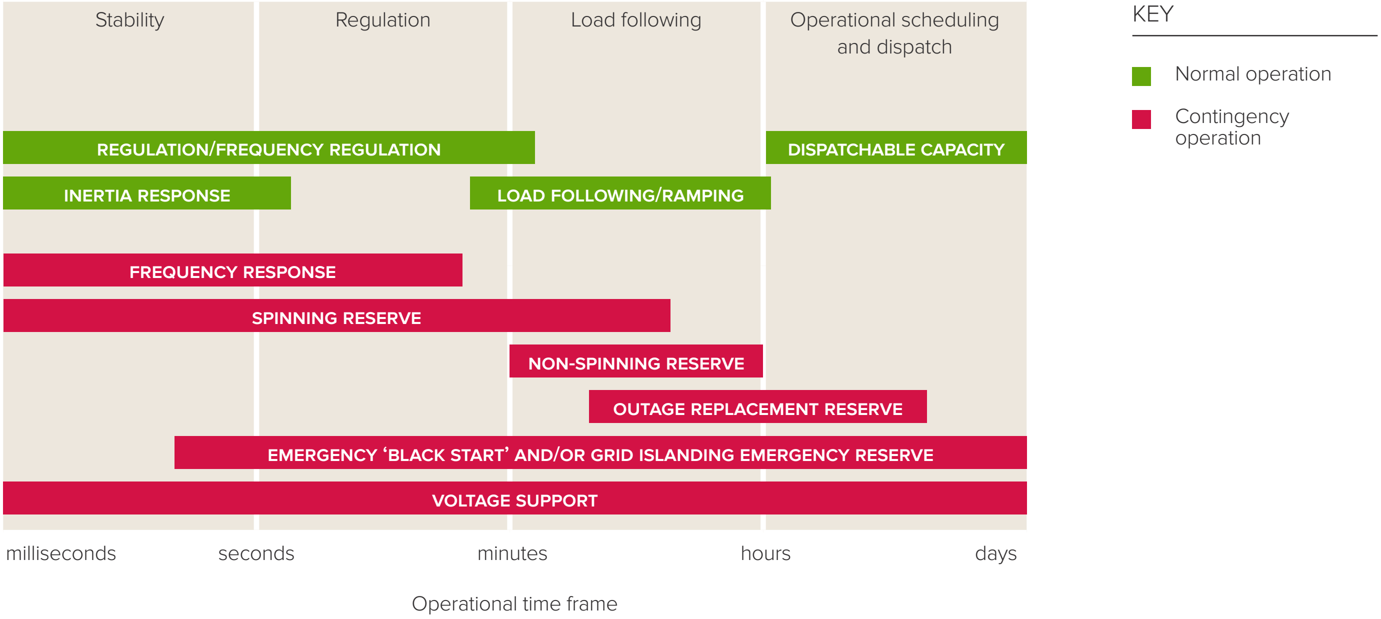
1. Tong, D, Farnham, DJ, Duan, L et al. Geophysical constraints on the reliability of solar and wind power worldwide. Nat Commun 12, 6146 (2021). See https://doi.org/10.1038/s41467-021-26355-z.
2. Brown P, Botterud A, The Value of Inter-Regional Coordination and Transmission in Decarbonizing the US Electricity System, Joule (2020). See https://doi.org/10.1016/j.joule.2020.11.013.

FIGURE 1

Operational duty cycles provided by Compressed air energy storage and other energy storage plant options.

Bulk storage plants, once built can provide all below duty cycles



Source: Energy storage applications (source: EPRI, Robert Schainker).
Note: All boundaries of regions displayed are approximate and chart axes are not linear.

Modelling plays an important role in identifying optimal scenarios for the future. For example, modelling carried out in the US has indicated that power-to-gas-to-power energy storage could be a viable long-term storage option, used synergistically with short-term storage such as batteries that deal with short-term power fluctuations[3].

Power-to-gas-to-power storage might typically involve creating hydrogen from electricity, storing it, and then converting it back into electricity when needed. Modelling also indicates that lowering the cost of long-term storage is better for overall system costs than lowering the cost of short-term storage.

While natural gas remains in the system, it is challenging to incentivise the development and deployment of long-duration energy storage solutions. Specifically, a marginal capacity expansion approach, where natural gas co-exists with renewable generation, is very different from creating a least-cost system with no natural gas. As natural gas is entirely phased out, the final 20% of emissions reductions dominates the future system architecture. There is a risk of failing to produce reliable, least-cost systems to the timescales required by net-zero targets if the market is left to deliver them without intervention from government.

Market restructuring is likely to be required to create appropriate incentives and avoid the market driving the system towards needlessly expensive solutions. The development of markets and supply chains, and the implications for policy, are discussed in Chapter 5.

There is potential to repurpose existing infrastructure assets in various ways, but it is uncertain the extent to which this will occur. For example, technologies could be repurposed to use alternative fuels such as hydrogen or ammonia instead of fossil fuels; this is discussed further in Chapter 4. Existing power plant locations could be used to locate new storage plant, or existing distribution or assets reused.

Grid operation and modernisation

Energy storage technologies can deliver a range of system requirements to help maintain a stable and reliable grid, in addition to providing dispatchable power. One example is frequency regulation: as the form of generation moves from spinning turbines which have a large inertia to wind and solar, energy storage can instead play a role in regulating grid frequencies. Other types of grid services that energy storage can deliver include voltage support, grid congestion management, 'black start' and peak shaving. Energy storage is also valued as a transmission asset, allowing transmission deferment in substation upgrades.

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[3] Tong, D, Farnham, DJ, Duan, L et al. Geophysical constraints on the reliability of solar and wind power worldwide. Nat Commun 12, 6146 (2021). See https://doi.org/10.1038/s41467-021-26355-z.

Figure 1 illustrates the range of services that energy storage technologies can provide, for both normal operation and contingency operation. While these ancillary services are far less technically demanding than bulk storage, they are the opening act for integrating significant storage into the grid.

Increasing levels of distributed energy generation such as wind and solar energy in conjunction with battery storage, as well as rapidly changing domestic and commercial demand, require a two-way grid that can deal with instantaneous changes in flow direction. Infrastructure that was put in place decades ago is coming to an end of its lifetime at the same time that technology improvements and climate needs are driving fundamental changes to asset operation. In the US, the transmission system has been modernised in recent decades as the result of a growth of independent power producers and the creation of independent system operators. In both the UK and US, modernisation is required as the nature of the distribution system changes. Grid modernisation will enable resilience to natural and man-made disasters by providing good visibility and control of the distribution system, with good cyber controls and security in place and the ability to respond quickly to rapidly changing conditions. As well as the traditional engineering skills and capabilities, a workforce will be needed that can understand the application of advanced technologies and interpret and respond to the reams of data coming from the distribution system. It is likely that the grid will continue to play a key role in the interconnection between generation and customer load.

The UK government has committed to 40 GW of offshore wind connected by 2030. In a 60 GW peak system, this will have a big impact on its operation. The UK's grid operator, National Grid ESO, is addressing how the net-zero system might operate in the future, and how flexibility and reliability can be achieved through energy storage and interconnectors. The deadline to end sales of new petrol and diesel cars by 2030[4] requires the grid operator to prepare the grid for substantial increases in electric vehicle charging. In the nearer term, the grid operator has set an ambition to be able to operate the GB grid without carbon sources to balance or manage it by 2025.

Regulation

The regulatory and political frameworks under which the energy system is delivered in the US and UK must be suitable for driving the transition towards a high-renewables grid with flexibility provided by storage and/or dispatchable backup.

In the UK, assets are privately owned and players are licensed, with licence rules set by the regulator, Ofgem, and the government. The electricity system has traditionally been divided into three areas: networks, the wholesale generation market and the retail market. Networks comprise the transmission companies who own the major transmission lines (National Grid in England), and distribution network operators, who take electricity from transmission lines and link it to homes and businesses. Network companies are regulated using incentive regulation, rather than the US rate-of-return approach. Retail suppliers provide electricity directly to homes and businesses. They operate competitively without linking to particular parts of the network, and some may own generation assets, so there is some degree of vertical integration. Recent years have seen changes in this arrangement: less vertical integration as renewables generators come on board alongside a greater number of suppliers selling electricity on the open market. It is uncertain what form a licence for energy storage might take, and whether it will be treated as generation or supply.

In the US, the system is more decentralised and is owned by a mix of public and private entities. Overall US energy policy is set by the federal government, but the Federal Energy Regulatory Commission (FERC) has limited power relative to its UK counterpart, Ofgem. The transmission system varies across the country, with two major grids – the Eastern and the Western – and two smaller ones – Alaska and Texas. Most independent system operators represent groups of states, such as PJM Interconnection in the mid-Atlantic region, while some are single-state. Retail suppliers provide power in a regulated way to end-users and have a monopoly in some states; some also generate electricity. There is variation in approaches to regulation between states, and differing levels of commitment to decarbonisation. It is possible that a quasi-federal approach could develop as decarbonisation becomes a higher priority for the new US administration.

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4. UK Government, November 2020. Government takes historic step towards net-zero with end of sale of new petrol and diesel cars by 2030. See http://www.gov.uk/government/news/government-takes-historic-step-towards-net-zero-with-end-of-sale-of-new-petrol-and-diesel-cars-by-2030, (accessed 10 November 2021).

While the US and UK energy market structures have served their purpose in bringing forward investment, including greater renewable generation over the last decade, it is possible that private markets will not achieve net-zero targets without some form of intervention. It is not clear how markets should be restructured, but this will need to happen within the next three to five years. The importance of incentivising investment in energy storage technologies and developing markets and supply chains is discussed further in Chapter 5.

It is not clear how interconnectors should be regulated. The UK has in the past been under-connected and is unique in Europe in having purely private interconnectors, which has led to market failure. Most interconnectors in Europe are state funded across different transmission companies. In recent years, a new mechanism based on a ‘cap and floor’ methodology has encouraged interconnector investment although Brexit has slowed this. The idea of a Europe-wide renewables interconnector, made possible by the reduction in the cost of offshore wind, has been raised in the past, but the level of cooperation among countries that is needed to create a more integrated grid, fit for purpose for net-zero, presents an enormous challenge.

Regulation has in the past treated the electricity system as a closed system, with the legal responsibilities of the regulator based purely on the electricity system. There is a further question about how to regulate a more complex energy system with cross-sectoral coupling.

3. Introduction to storage technologies

A diversity of energy storage requirements will be needed for the future grid, with durations from seconds to days, weeks and months; storage capacities from kWh to hundreds of TWh, and power capacities from MW to tens of thousands of MW (Figure 2). In the UK and US, a range of different energy storage technologies are under consideration, including electro-chemical, mechanical/kinetic, thermal and hybrid storage. Solutions exhibit a range of technological maturities as shown in Figure 3.

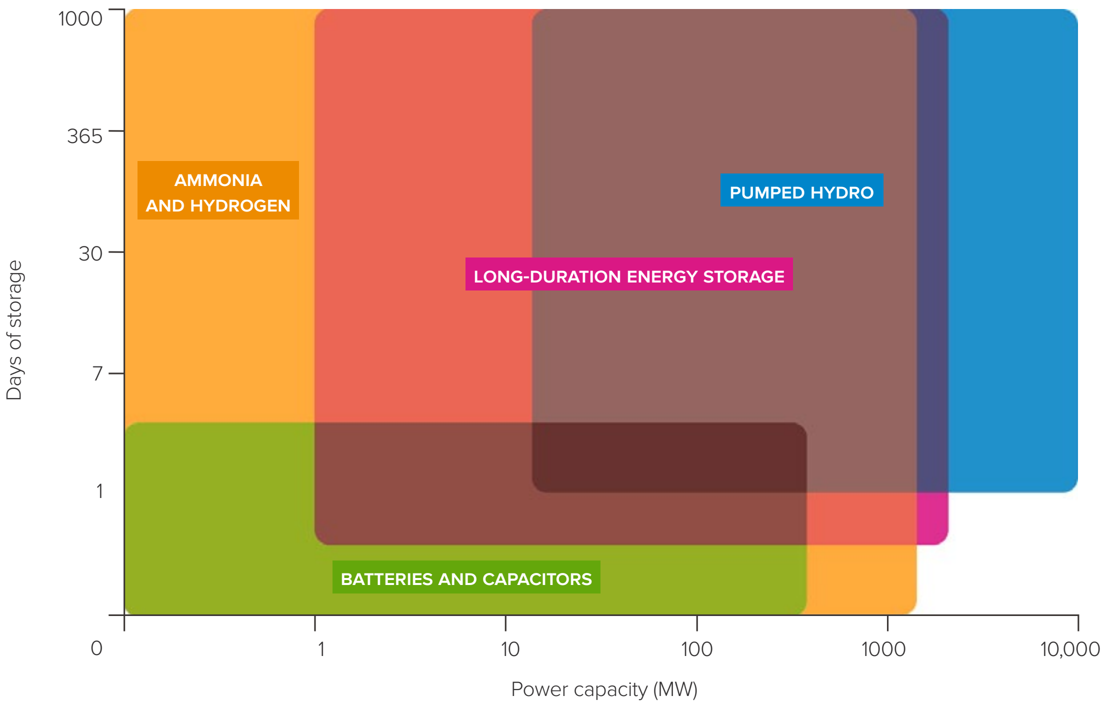
To date, much of the research and development effort has focused on batteries as a result of growing market demand in end-uses such as transportation. Batteries dominate current and planned deployment of energy storage. There has been less focus on longer-term storage technologies needed for the grid, and there is a gap in established medium- and long-term storage technologies for grid-scale applications (Figure 3).

Cost and the level of potential return is a major barrier to investment when compared to more traditional utilities resources, but there is potential to reduce costs through research and development activities for all types of storage.

Advances in battery technologies have already led to increases in power and duration and decreasing costs. For example, lithium-ion battery costs have been declining by about 20% year on year, although this decrease is plateauing. If a battery has high utilisation, its value is realised by cycling the battery (charging and discharging) many times, for example in frequency regulation. Lithium-ion battery systems currently cost around $300/kWh, with potential to bring costs down to around $200/kWh through innovation. If the main purpose of energy storage is to provide resilience, utilisation will be low and the target cost needs to be closer to $10 – 100/kWh.

FIGURE 2

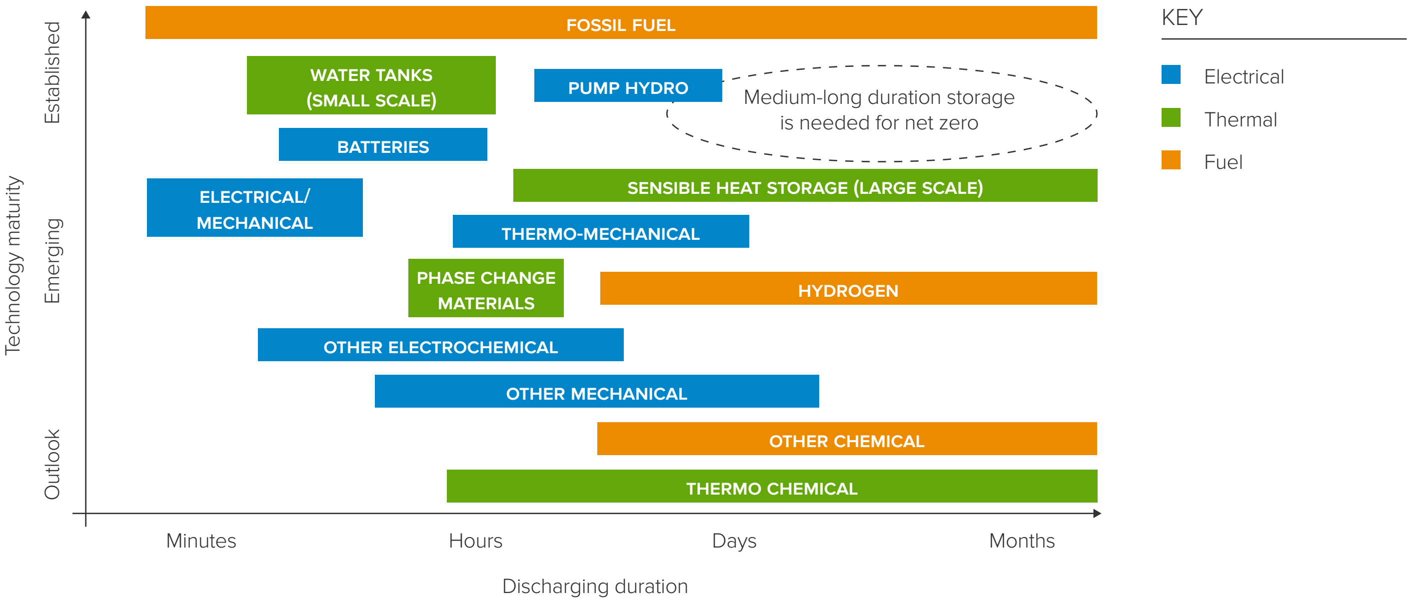
No 'one size fits all' solution



Note: All boundaries of regions displayed are approximate and chart axes are not linear.

FIGURE 3

Energy storage technology maturity



Source: EPSRC

Flow batteries and other types of energy storage are likely to be more cost-competitive than batteries for longer duration applications. For example, the cost of hydrogen, a possible form of long-duration storage, is expected to decline by about 50% in coming decades.

In addition to cost, energy density and power density are two important performance metrics. Energy density is essential for energy storage in transportation, but less so for stationary applications which do not have the same weight and space restrictions. Power density is more critical for grid-scale storage when a rapid response is needed, such as short-term balancing for primary frequency regulation. Roundtrip efficiency and lifecycle are also key metrics, as are safety, sustainability, predictability and operating temperature.

In both the UK and US, public funding programmes for energy storage are underway, as part of broader energy system research and development support.

In the absence of certainty about what technologies will emerge as viable solutions, both the UK and US recognise the need to support a portfolio of different solutions rather than ‘picking winners’.

In the UK, the Faraday Battery Challenge is a £318m national initiative funded by UKRI which brings together the research and industrial communities to tackle challenges from research and development to manufacturing and scaling-up supply. As part of this initiative, the UK Battery Industrialisation Centre is an open-access facility providing Giga-factory capability at industrial production rates.
The UK’s Supergen energy storage programme looks beyond batteries to other types of energy storage and has included a road mapping exercise[5]. Other energy storage programmes are currently underway, including on thermal storage, mechanical / kinetic storage and hybrid storage[6,7].

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5. Supergen Energy Storage Network+ and Birmingham Energy Institute, Energy Storage Roadmap. See http://www.ukesr.supergenstorage.org/chapters/introduction (accessed 10 November 2021).
6. For example:, ‘Energy storage for low carbon grids’, ‘Integrated market-fit and affordable grid-scale energy’ (IMAGES), and the EPSRC Centre for Doctoral Training in Energy Storage.
7. UK Government, March 2021. Longer duration energy storage competition. See http://www.gov.uk/government/publications/longer-duration-energy-storage-demonstration (accessed 10 November 2021).

Similarly to the UK, the US has in the past focused its funding support on electro-chemical storage, with some pockets of funding for other technologies, provided by ARPA-E and other government departments. For example, the ARPA-E DAYS programme[8] funds storage in the tens to hundreds of hours duration, aiming to achieve a cost of 5 cents per kWh or less. In 2020, the US Department of Energy launched its Energy Storage Grand Challenge[9] to accelerate the development, commercialisation and deployment of next-generation energy storage technologies. Similarly to the UK, US research crosses the spectrum of technology development, manufacturing and scaling up and pilot projects that demonstrate use cases, as well as policy and workforce development. The US Department of Energy has targeted the development of a distributed energy storage system with an installed capital cost of less than $100 per kWh and a lifetime of greater than 5000 cycles, without degradation of power or storage capacity, to be comparable to pumped hydro which is typically capable of 20,000 charge and discharge cycles.

Many types of storage device encompass a complex interplay of materials, chemistry and engineering. It takes time to bring technologies from lab to market – perhaps a decade. There are, however, many fundamental materials challenges that can be brought to bear on energy storage. Furthermore, many technologies are modular, and therefore the potential to scale up is present. Manufacturing at GW scale must be reached for technologies to be competitive.

The US Department for Energy has summarised markets for deployment of seven transportation and energy storage technologies globally through to 2030[10]. It is expected that by 2030, annual stationary storage, excluding pumped hydro, will exceed 300 GWh, representing a 27% annual compound growth rate for grid-related energy storage and an 8% annual compound growth rate for use in industrial applications. Much of the growth is projected to be for four-hour hybrid configurations.

While markets for short-duration storage, such as batteries, already exist, a central challenge is bringing other storage technologies through to market at scale, so they are attractive to investors and will be ready to deploy when needed, despite the absence of a market and uncertainty about their value at the current time. This is discussed further in Chapter 5.

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[8] ARPA-E, DAYS (Duration Addition to electricity Storage) program. See https://arpa-e.energy.gov/technologies/programs/days (accessed 10 November 2021).

[9] US Department of Energy, Energy Storage Grand Challenge. See http://www.energy.gov/energy-storage-grand-challenge/energy-storage-grand-challenge (accessed 10 November 2021).

[10] U.S. Energy Information Administration (EIA) Annual Energy Outlook 2021 (AEO2021).

4. Storage technologies: challenges and future directions

The following chapter presents some of the key technology options for energy storage and discusses the science and technology challenges, developments to date and the future direction of travel.

Electro-chemical storage

Lithium-ion and sodium-ion batteries

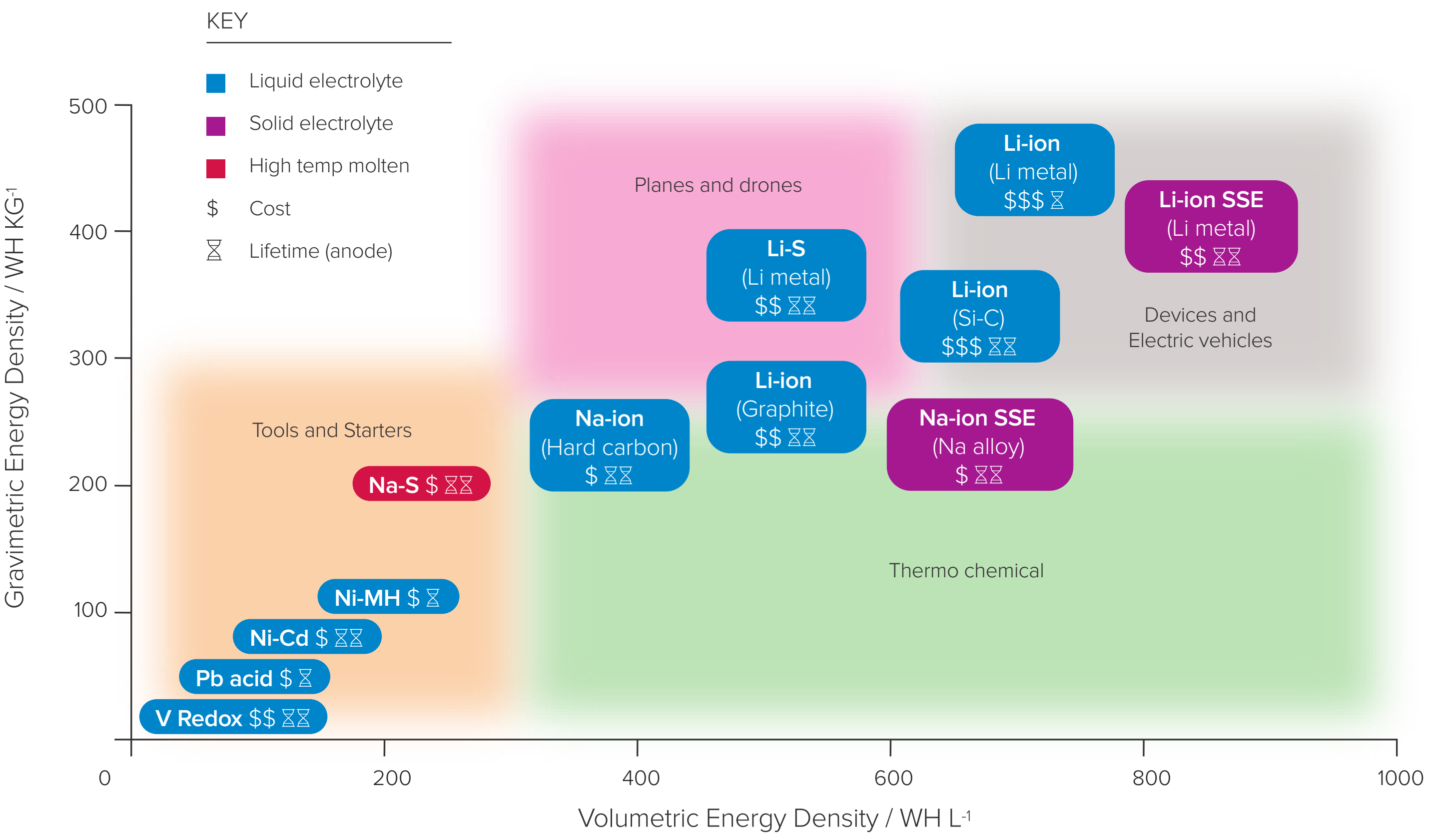
Lithium-ion batteries are made up of cells containing an anode, cathode and electrolyte, and are charged and discharged through chemical reactions. They have a storage duration of seconds to hours and are capable of providing power in a range from hundreds of kWhs up to tens or hundreds of MWhs. The scale of manufacturing capability is growing; a GW scale lithium-ion battery factory, such as the LG Chem factory in Wrocław, Poland which is capable of producing 25 GWh of batteries in one year.

In addition to arbitrage, lithium-ion batteries can be used for ancillary grid services such as frequency regulation and voltage stability. They can be used in 'black start' as generating capacity can be run up within minutes. They have a role in peak shaving and load levelling, on a timescale of hours. With micro-grids or local-off grid applications, batteries might be the totality of the storage solution.

Cost is a major barrier. Most of the development has occurred with automotive applications in mind that have a shorter timescale to recover costs: typically 10 years for an electric vehicle in comparison to 40 years in the case of the grid. Extending lifetime for grid applications is a further challenge.

FIGURE 4

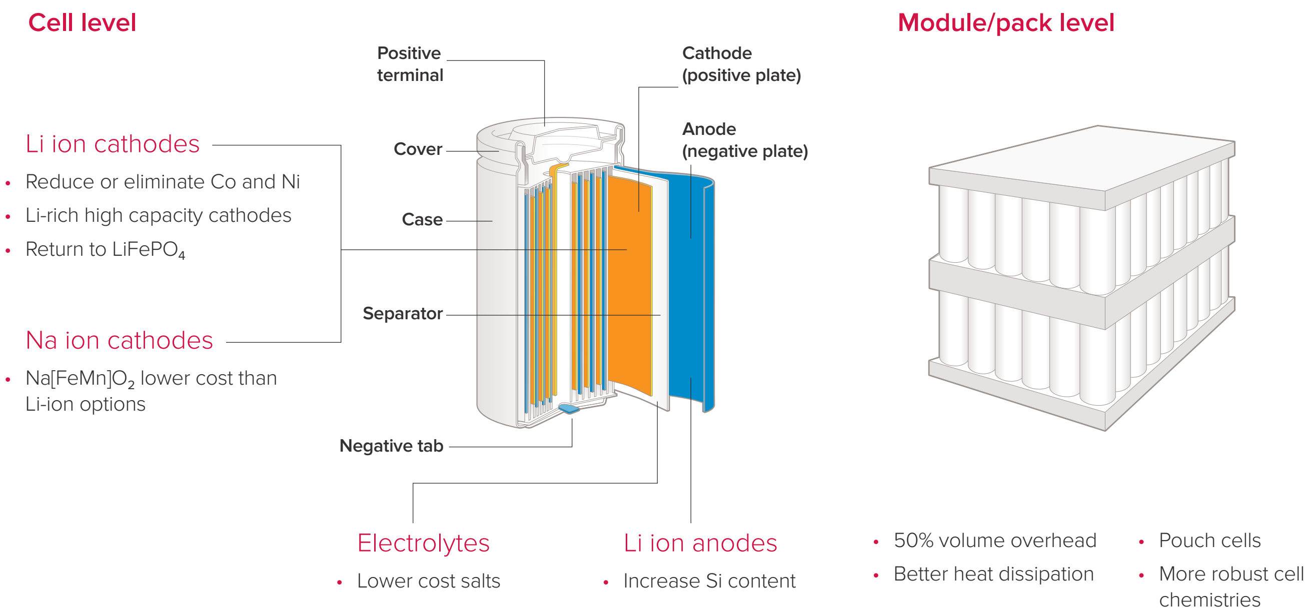
Battery performance, lifetime and cost



Source: Adv, Energy Mater. 2020,10,2001274

FIGURE 5

The road to lower cost and longer life: key areas to reduce battery costs and increase lifetime.



Cell level

Li ion cathodes

- Reduce or eliminate Co and Ni
- Li-rich high capacity cathodes
- Return to $LiFePO_4$

Na ion cathodes

- $Na[FeMn]O_2$ lower cost than Li-ion options

Electrolytes

- Lower cost salts

Li ion anodes

- Increase Si content

Module/pack level

- 50% volume overhead
- Better heat dissipation
- Pouch cells
- More robust cell chemistries

Sodium-ion batteries operate in a similar way to lithium-ion batteries, but with different materials in the anode, cathode and electrolyte. They offer an alternative to lithium-ion, which is the incumbent technology, and avoid the use of cobalt which is in short supply. As yet, there is no established sodium-ion battery manufacturing capability at scale. For sodium-ion batteries to displace lithium-ion, it will be necessary to drive down the costs of the cell's component parts: cathodes, anodes and electrolytes. Figure 4 illustrates how lithium-ion and sodium-ion batteries are vying with each other in terms of cost for grid-scale storage applications.

Further reductions in the costs of the cell's components are also possible for lithium-ion batteries. Optimising the design of modules and packs also presents an opportunity to reduce costs. Figure 5 indicates the different opportunities for cost reduction and longer life in lithium-ion and sodium-ion batteries. In addition, there is potential to drive up the scale and speed of manufacturing, so that more cells per hour can be manufactured in the same footprint of a factory. To date, the scale of manufacturing has been driven by the demand from automotive markets.

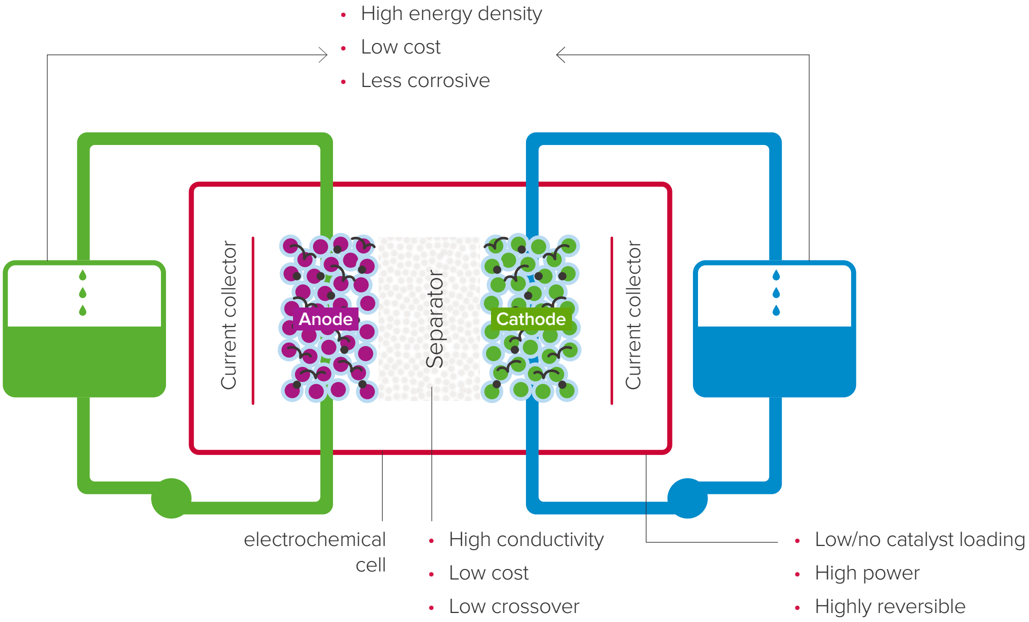
Flow batteries

In flow batteries, the electrolyte is contained in two tanks and pumped through the cell, which comprises a membrane held between two electrodes. In effect, energy and power are separated. Flow batteries offer longer discharge times than other types of batteries; the focus to date has been on making them competitive for typically 4 to 8 hours of storage. There is potential to reduce costs at many levels in both the tanks and the flow cells, through innovations in the materials used including the electrolyte, the cell or pack design, the manufacturing process and its ability to scale, and the overall system costs.

Increasing the size of the tanks provides the opportunity to scale up energy capacity independently of power. As the energy capacity increases, both the tank and electrolyte costs will increase relative to the cell costs. Figure 6 summarises some of the research challenges for the tank and chemicals, cell and membrane.

FIGURE 6

Flow battery development challenges: innovation needs to occur at multiple levels.



Source: Argonne National Laboratory

A systems approach to battery development

Multiple challenges make technology development a complex problem, requiring a systems approach. Challenges span the cost of materials and price volatility, supply chain issues for critical materials including their origin and availability to meet GWh requirements, manufacturing processes for cells, modules and packs that offer efficiency and the ability to scale up. Ensuring that a battery performs as required by its application and use case is a further challenge, and therefore understanding how it will be used and how it might be commercially viable is also important. Can it last for twenty-five years rather than five years? How will local markets operate, and how will the technology work with local electricity pricing? Is a leasing model possible? How are different communities across the globe responding to climate change, and what will local solutions look life? A use-case perspective is therefore also vital; adaptive development will be required as different use cases emerge.

When considering the cost of different chemistries, it is important to examine the context in which the battery will be used and how it will operate within a system; for example, the cost of sodium/sulphur is low but the battery only works at high temperatures, which has implications for the package costs. Lead-acid has been used for many years in batteries – it is cheap and can be recycled but has limited cycle life so is not suitable in uses requiring long lifetimes.

A whole-life approach to batteries

It will be vital to continue to increase the longevity of batteries beyond 10 years, and to reduce costs without sacrificing lifetime. Lifetime influences cost since it affects speed of wear-out and replacement rate. Lifetime is an important consideration in relation to stack services, where a battery is providing many different services.

Two key challenges are present in relation to battery longevity: understanding the relationship between cycle life and calendar lifetime, and being able to predict lifetime prior to deployment. Accelerated lifetime prediction must play an important role, enabled by artificial intelligence and machine learning. Solving these challenges requires a fundamental understanding of materials and how they behave according to the chemistry or type of technology. A small change in the chemistry within a device can have a large impact on performance.

There is potential to recycle or reuse batteries, or focus on designing batteries with a much longer lifetime. Predicting the second life of a battery so it can be reused is especially challenging as it depends on how it has been used in its first life. Valuing that asset is difficult when lifetime is uncertain. Being able to locate a fault within a battery stack and repair it is a further challenge for batteries.

Design and manufacture for recycling or reuse needs to be addressed upfront. For example, batteries could be packaged so that they can be easily taken apart. Research in the US is examining the potential to reuse electric bus battery packs, taking them apart to determine the fraction of the cells that are viable for reuse. The Faraday Institution is also investigating ways of recycling batteries. Given the safety issues, recycling would need to be done in a safe, automated way, perhaps by the manufacturer, rather than outsourced to a developing country.

Supply chain issues

The availability of raw materials affects the viability of certain battery technologies. It is becoming apparent that there is a sufficient supply of lithium in the world; however, security of supply is an issue and of concern in the both the UK and US as they do not mine significant amounts of lithium. Technologies that avoid using cobalt or nickel will be preferable. Sodium-ion batteries replace cobalt in their cathodes with iron and manganese which potentially makes them of value, as long as they can be developed as a viable alternative to lithium-ion batteries.

Cross-sectoral coupling: vehicle-to-grid

There is potential to connect vehicles to the grid as auxiliary storage. A vehicle charging system would provide flexibility for households and may be useful for managing variability on the low-voltage distribution system. However, it will not manage variability at seasonal or diurnal timescales.

If all of the c.150 million light-duty vehicles in the US were electrified, 10% of each battery's 100 kWh charge would provide 1.5 TWh, which is commensurate with approximately 3 hours of the country's average 0.5TW power demand.

Vehicles often sit idle for many hours each day. What would be the impact on their batteries of more frequent and perhaps deeper grid-driven cycling? What business models would make it worthwhile for individuals to sell back electricity to the grid, albeit with the challenge of more rapid battery degradation? Is it worth their while to buy a bigger battery for this purpose? Would the income generated from selling back electricity to the grid compensate for the effective decrease in lifetime due to increased battery cycling? Consumers are currently buying electric vehicles even if they do not pay back.

There may be niches where vehicle-to-grid is economic, for example for bus depots and owners of large vehicle fleets. Car batteries with longer lifetimes may be designed specifically for vehicle-to-grid connection in future.

Broader issues also have a bearing: the affordability of electric vehicles is an issue, as is their viability for individuals who do not have off-street parking or access to charging points. Vehicles may in future be more highly utilised if models of vehicle ownership shift towards shared asset models, for example, with the advent of autonomous vehicles or in developing countries, where shared assets models are more economically efficient. In the US and UK, consumer preferences are important unknowns.

Alternative energy storage methods

Thermal energy storage and thermo-chemical energy storage

Thermal energy is at the heart of the energy supply chain, with 90% of the current energy budget centred around heat conversion, transmission and storage. As the amount of renewable generation increases, more energy conversion steps will be needed: increasing from about three conversion steps today to up to about seven conversion steps by 2050. Therefore in the future, overall energy efficiency with respect to primary energy sources, whether solar or wind, will be considerably lower than energy efficiency today, with energy lost as waste heat at each conversion step. But more than 50% of that final energy use is for heating. Is it therefore possible to recover the thermal energy that would otherwise be wasted in conversion and store it? This would help to reduce energy demand, and therefore the scale of generation, transmission and other types of storage asset that would otherwise be required.

Thermal energy storage potentially has a wide range of applications in power, buildings, district heating and cooling, cold chain and industry. It can provide flexibility for the grid in a number of ways, including demand shifting, variable supply integration, sector integration and network management as well as seasonal storage[11].

There are three main types of thermal storage: sensible heat storage (involving a change in temperature), latent heat storage (requiring a phase change process) and thermochemical heat storage (requiring reversible chemical reactions or a sorption process).

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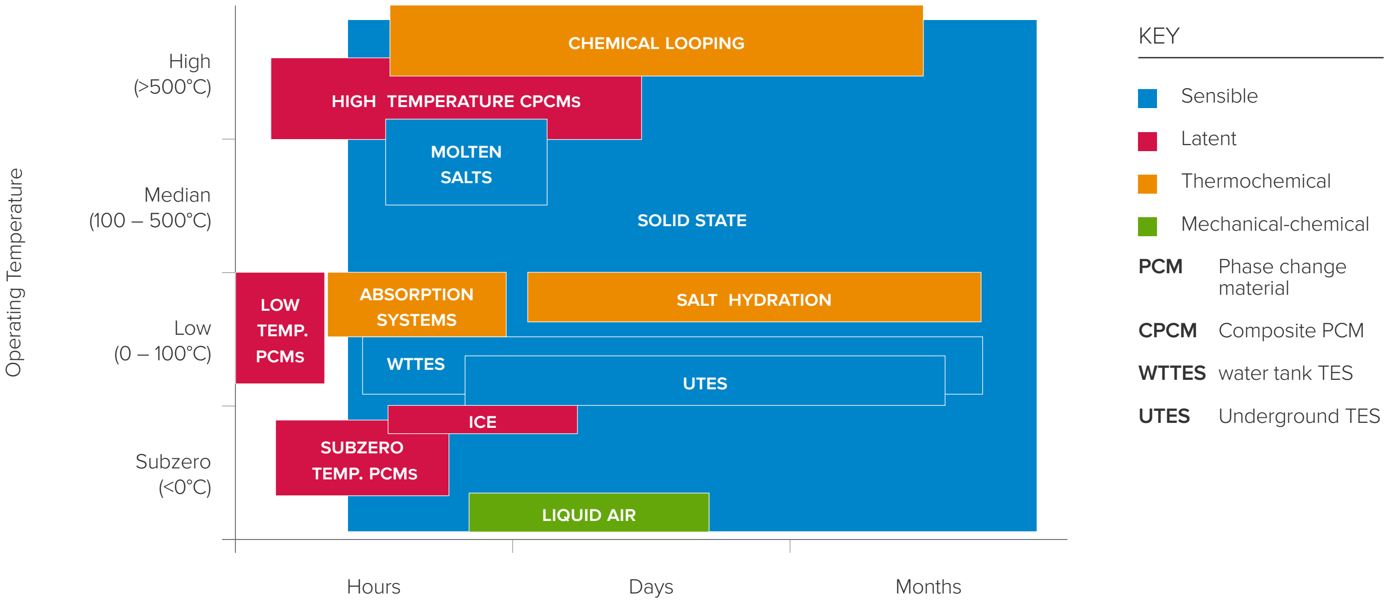
[11] IRENA (2020). See http://www.irena.org/publications/2020/Nov/Innovation-outlook-Thermal-energy-storage (accessed 10 November 2021).

FIGURE 7

Thermal storage technologies and applications



Source: IRENA (2020) Innovation outlook: Thermal Energy Storage

Sensible heat storage has already been used for hundreds of years and is at high TRLs; one example is solar heat storage for concentrated solar power. A Phase Change Material (PCM) heat store for curtailed wind is one type of latent heat storage which could be used for space heating. PCM technologies are currently at TRLs of between two and five. Thermochemical heat storage is at a low TRL, typically between one and three; one example is sorption heat storage for district heating and cooling. The various technologies have differing operating temperature and duration characteristics (Figure 7).

A number of commercial thermal energy storage plants and pilots exist. For example, a 50MW/250 MWh commercial liquid air energy storage plant is currently under construction in the UK by UK Highview Power, due for completion in 2023. Siemens Gamesa is currently commercialising an electrical thermal energy storage plant with power up to 100 MW and capacity up to 2000 MWh. An industrial-scale composite PCM plant has been running since 2016 as a partnership between Jinhe Energy, Birmingham University and Kelvin Thermotech, with power 6 MW and capacity 36 MWh.

PCMs are also being developed in a commercial venture between CRRC, Birmingham University and Kelvin Thermotech as a way of replacing diesel-powered transport refrigeration. In the UK, the use of thermal energy storage in electric vehicles is being developed, by generating heat or cold in stationary mode rather than on-board vehicles, with corresponding efficiency gains and increases in range.

The International Renewable Energy Agency (IRENA) has set out current and projected thermal energy storage capacities[12]. For heating, global thermal energy storage capacity is estimated to be 199 GWh at the current time, comprising mainly building and district heating applications, with a small amount in industry. In power applications that primarily use molten salt for concentrated solar power at the current time, the capacity is projected to increase from 21 GWh to more than 500 GWh by 2030. For space cooling, capacity is projected to reach 26 GWh by 2030. Today cooling accounts for about 10% of electrical energy consumption, but this is set to increase in the future as a result of climate change and increased data centre capacity, while heating demand is likely to decrease. Energy for cooling could exceed heating in 2060 and is therefore an important consideration.

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[12] IRENA (2020). See http://www.irena.org/publications/2020/Nov/Innovation-outlook-Thermal-energy-storage (accessed 10 November 2021).

There is potential for thermal storage to be coupled with other storage methods, requiring a whole-energy system approach.

Compressed air energy storage

Compressed air energy storage (CAES) systems typically compress air to high pressure and store it in cylinders or underground. When the energy is needed, the high-pressure air is expanded through a turbine to produce electricity. Adiabatic compressed air systems store the heat generated during compression to re-use during expansion, rather than burning gas to prevent freezing during expansion.

Large-scale plants have been operated at a range of timescales (typically hours) and power (typically hundreds of MW), in a range of underground geologies: salt caverns, porous rock in a geothermal zone, and disused coal mines. There are currently only two commercial-scale plants in operation in the world (both of which burn gas). In the US, the McIntosh plant has 226 MW capacity and 26hour duration and operates with an air store that uses a solution-mined salt cavern. In Germany, the Huntorf plant has 320 MW capacity and 4-hour duration, and similarly stores air in a salt cavern. CAES is potentially a viable technology for energy storage and it also offers a range of ancillary grid services, including for both normal operation and contingency operation. CAES offers the potential to build storage reservoirs capable of many discharge hours at lower capital costs per discharge hour than many other storage technologies.

CAES requires the marriage of underground geological expertise with above-ground turbomachinery expertise. In the US and elsewhere, porous rock plants using sandstone formations are currently used to store natural gas by the oil and gas industry; about 400 storage systems currently exist in the US. These have known geological characteristics and could be used to store compressed air.

New ways to design materials for pipework would be needed for air as it contains corrosive elements. There is also potential to optimise turbomachinery design. For example, it may be possible to size the compressor and expansion turbine systems so that the timescales for compression and expansion match the off-peak availability of generation and peak demand respectively; peak demand typically has shorter hours than off-peak generation availability. This is not possible for batteries.

Hydrogen and ammonia – generation and storage

Introduction to hydrogen

Interest in hydrogen technologies have increased over the last five years, reflecting a recognition of hydrogen's potential usefulness in a range of applications beyond fuel cells. In addition to long-term storage and grid balancing, or as an alternative fuel to natural gas, it also has application in the chemical industry, and as a feedstock in steel production. It also offers flexibility through cross-sector coupling. The following discussion covers technologies for green hydrogen production; blue hydrogen production methods are not discussed in detail[13].

Hydrogen generation - electrolysis

A number of different hydrogen electrolysis technologies exist at different levels of technology readiness. Alkaline water (KOH) electrolysis is a relatively mature technology with MW-scale stacks and 100 MW-scale systems in existence. Proton exchange membrane (PEM) technology emerged in the last decade and is available commercially at MW-scales, but fewer facilities are in existence. Solid oxide technology, which operates at a higher temperature but enables higher efficiency, is emerging with 100kW-scale systems in operation, but the market is not yet well developed. Low-temperature KOH/PEM hybrids are also emerging, but their viability relies on the availability of more stable membrane materials.

PEM electrolysis is expensive as it was originally developed for life support applications, at small scale and high reliability. It is cost-competitive for certain applications, such as heavy-duty transport, industrial processes, submarines, weather balloon filling and power plants. Markets are growing as the scale of production increases. In future, it could become cost-competitive with battery storage in long-duration grid-scale applications.

The total cost of ownership of large-scale electrolysis plants comprises operating costs, determined by the cost of electricity, and capital costs. There is potential to reduce capital costs through technology development and increased efficiencies, improvements to the manufacturing process, use of materials, system-scale design and power electronics for optimisation. It is economically worthwhile to recover and reuse precious metals used in PEM electrolysers such as platinum, and to reduce the amounts of metals such as iridium, which is used as a catalyst. While it is possible to make and operate a large electrolysis unit, these are not yet being manufactured at scale. Much of the opportunity lies in scaling up production of the units.

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[13] For example: BP plans for UK's largest hydrogen project. See http://www.bp.com/en/global/corporate/news-and-insights/press-releases/bp-plans-uks-largest-hydrogen-project.html (accessed 10 November 2021).

More research is needed to explore the benefits and uniqueness of each electrolyser technology, and how the different technologies can be combined in a production portfolio that allows optimal operation on a large-scale site, such as the Asian Renewable Energy Hub[14] which is aiming for 9.9 million tonnes of green ammonia production per year, using a 26 GW hybrid wind and solar plant.

Hydrogen generation and use - solid oxide technologies

Fuel cells are electro-chemical devices that combine hydrogen and oxygen to produce electricity, heat and water. Solid oxide cell technology offers particular promise due to its high efficiency at a range of scales and its flexibility to run on natural gas, ammonia or hydrogen. Applications include heavy-duty vehicles, shipping and rail, and domestic heating. While the efficiency decreases when hydrogen or ammonia are used in place of natural gas, the cost per kW is greatly reduced as the system complexity is lower. A solid oxide fuel cell could potentially be developed to work with any of the three fuels in the same system, reducing the risk of assets being stranded as natural gas is phased out and making the system suitable as a transition technology.

Although not yet as mature a technology as PEM electrolysis, solid oxide cell technology offers certain benefits. For example, it is reversible so can be run backwards as a highly efficient electrolysis system to produce hydrogen as well as operating in the more conventional way as a fuel cell. Manufacturing capacity for this application can build on existing manufacturing facilities already used to deploy fuel cells commercially, offering the potential to scale up production at pace.

The UK company Ceres has patented a solid oxide fuel cell and is exploiting the intellectual property in different applications and with different partners around the world. Ceres has developed a metal-supported low-temperature solid oxide cell which, as a result of the choice of materials, can run at relatively low temperatures (about 600°C), and is robust, straightforward to manufacture and can easily be integrated into stacks.

Hydrogen storage

The use of hydrogen for long-duration grid storage is a promising option; typically hydrogen would be generated during times of excess renewable energy generation and stored underground until it is needed to generate electricity. Hydrogen storage plants could operate at a seasonal timescale and potentially provide TWh of energy capacity per year. The cost of hydrogen storage depends on the costs of making hydrogen, storing it, and converting it back to power. The relative costs of input and output depend on their respective ratings, which can be chosen independently. Demonstration of an integrated system is needed at scale, and some further development is required, particularly of conversion to/from power, as well as on hydrogen transport and distribution

The variety of market options for hydrogen make it possible for a dynamic market to emerge, whereby if there is sufficient hydrogen stored and it is possible to replenish it in time, storage costs could be offset by selling hydrogen dynamically.

Challenges for hydrogen technologies

The development of new materials that are more active, more durable and lower cost could play a role in driving down the cost of hydrogen production and storage. This might include a focus on the catalysts and membranes used in electrolysis and fuel cells, or on porous media for storage, for example.

Lifetime is an important metric for hydrogen technologies but increasing lifetime may conflict with cost reduction in certain situations. For example, reducing the cost of cells used in electrolysis through materials *thrifting* – by creating thinner membranes, or avoiding critical metals – can impact durability. Innovation in material compositions and architectures will be vital, as will the development of protocols for testing durability.

A system perspective is needed to understand the role of hydrogen in relation to the grid: how will hydrogen be generated on and off the grid? What flexibility, rapid-response grid services such as storage can it provide for the operator? How can it be integrated with wind and solar generation directly to produce green hydrogen? What capacity will be needed, but also what will operating schedules look like over time?

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[14] The Ammonia Energy Association. Green ammonia at oil and gas scale: the 15 GW Asian Renewable Energy Hub, 2020.

Introduction to ammonia

Ammonia is often conflated with, and subsumed into, hydrogen, but it is very different. Ammonia and hydrogen are two complementary zero-carbon fuel partners that must work in synergy as fuels and storage. A primary use of ammonia has been in fertiliser production, but emerging uses in other sectors are driving market expansion. It could be used as a hydrogen carrier, in energy storage, and as a fuel in the maritime sector and in electricity generation.

Ammonia generation

Ammonia is produced from nitrogen and hydrogen using the Haber-Bosch process. Currently most ammonia is not produced in a carbon-neutral way, and in addition, the hydrogen used in its production requires steam-reformation or coal which also generates emissions. However, GW-scale green ammonia production plants are beginning to come online as a result of growing demand. For example, Yara manufactures ammonia for use in mineral fertiliser production, its core business, but it is also developing businesses in the energy sector and shipping. Yara recently announced plans to retrofit an existing large-scale ammonia production facility in Norway as an entirely green production facility[15].

Scaling up the production of green ammonia will help unlock its use as a fuel or for energy storage in a renewable energy system. There is potential to co-locate ammonia production with renewable energy in countries with stable weather and export it in liquid form. The focus to date has been on increasing the rate of production using catalysts that work with continuous supplies of hydrogen, but that is a challenge when hydrogen is created using renewable energy. Alternatively, catalyst development for batch synthesis will involve using a different industrial process with a completely new catalyst structure. The cost of green ammonia is dictated primarily by the cost of green hydrogen.

Ammonia storage

Ammonia has a higher energy density than hydrogen and condenses at a much higher temperature, which makes it attractive for transporting and storing energy, as well as in maritime applications. There is also existing commercial infrastructure for shipping it. A large amount of anhydrous ammonia is already stored in US states such as Iowa for agricultural purposes. If ammonia is used as a hydrogen carrier for export purposes, it can potentially be cracked back into hydrogen where the hydrogen is needed. When a high level of hydrogen purity is required, the cost of cracking and purification is greater than for applications where lower purity is acceptable.

Uncertainty remains about the value of ammonia for long-term energy storage, its role in the future energy system, and the flexibility benefits that arise from cross-sector coupling. As yet, there is no clear market price for ammonia for long-duration storage which is needed to inform the economics of ammonia production plants. It is also uncertain what impact cross-sector coupling would have on market price.

Ammonia and hydrogen as low-carbon fuels

The use of low-carbon fuels in power generation

The use of low- or zero-carbon fuel for power is not new: the technology is available and has been applied in various industries for decades. But the concept of using low-carbon fuels such as hydrogen, ammonia or biofuels specifically for power generation in GW-scale power plants is new. The idea of repurposing existing power plants that are already connected to a gas distribution network is attractive, but there are a number of technological and system challenges. Research and development activities would need to address the optimisation of outputs and efficiencies from power plants that burn low-carbon fuels, and to investigate the infrastructure that is required for storage, production and transportation of low-carbon fuels. The use of low-carbon fuels in existing power plants would require upgrades to pipes and valves, safety systems, control systems, combustion systems and emissions handling.

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[15] Yara partners with Statkraft and Aker Horizons to establish Europe's first large-scale green ammonia project in Norway 2021. See http://www.yara.com/corporate-releases/yara-partners-with-statkraft-and-aker-horizons-to-establish-europes-first-large-scale-green-ammonia-project-in-norway/ (accessed 10 November 2021).

It is currently possible to generate power by burning a mix of ammonia and fossil fuels, with lower carbon emissions than if the fossil fuel was used alone. If ammonia can be made from renewable energy and combusted efficiently in a turbine, it could potentially provide a whole new toolkit to deploy in a renewable energy system. However, there is a risk that the combustion process produces NO_x emissions, which is a challenge to mitigate. Notwithstanding, Mitsubishi has recently announced its intention to develop a 40 MW ammonia-powered gas turbine with a low-NO_x combustion process. Japan published its Fuel Ammonia Road Map in February 2021 which sets out its ambition to develop energy generation using 100% ammonia turbines and to supply ammonia to its neighbours by 2050[16]. This will require a huge scale-up in ammonia production to supply many mega-tonnes of demand, just for this part of the world. There are also examples of commercial-scale gas turbines that run on a mixture of hydrogen and fossil fuel. The costs of such plants are dictated primarily by the cost and availability of the low-carbon fuel.

Oxyfuels are a further type of low-carbon fuel. Oxygen is created from electrolysers, and there is potential to create a fuel with a mix of hydrogen and oxygen if the market exists. Oxygen could also be used in CCS, although it cannot be used in existing gas turbines.

A number of different technologies could use low-carbon fuels for power generation, including turbines, fuel cells and internal combustion engines. The relative costs and efficiencies of turbines versus fuel cells are highly context-specific. Four-stroke internal combustion engines are emerging as a competitor to gas turbines in relation to cost and flexibility.

The use of low-carbon fuels in transportation

Decarbonisation targets for transport systems will drive the development of low-carbon technologies. For example, Europe has a target of 90% reduction in transport emissions by 2050, relative to 1990 levels. Electrification is the most likely option for light-duty transportation. For heavy-duty transportation such as trucks, buses and ships, other energy vectors such as hydrogen or ammonia may well be preferred as they allow for increases in range and decreases in recharge times relative to batteries. Producing on-board storage, whether a battery pack or hydrogen storage, is a key technical challenge. The use of low-carbon fuels in aviation is also being explored[17].

As for all applications, the whole-life environmental impact of transportation needs to be considered, not just the reduction of emissions at point of use. Batteries and fuel cells have an embedded environmental impact associated with their production and end-of-life. There is potential to recycle and reuse, to drive down costs and minimise environmental impacts.

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16. Ammonia Energy Association 2021. See http://wwwww.ammoniaenergy.org/articles/japans-road-map-for-fuel-ammonia/ (accessed 11 November 2021).
17. For example: Reaction Engines, 2021 Reaction Engines, STFC engaged in ground-breaking study on ammonia fuel for a sustainable aviation propulsion system: Reaction Engines See https://www.reactionengines.co.uk/news/news/reaction-engines-stfc-engaged-ground-breaking-study-ammonia-fuel-sustainable-aviation-propulsion-system (accessed 11 November 2021).

5. Advancing the science while bringing solutions to the market

Sustainability and safety

Energy storage and the circular economy

The wider environmental costs, including costs associated with greenhouse gas emissions, are not yet incorporated in 'total cost of ownership' or 'levellised cost' models for the energy system. Batteries are currently at a more advanced stage of development than other types of energy storage, but even so the environmental costs of batteries are imperfectly captured, if at all, and the value of second life is unclear. Therefore, there is no incentive to produce a product with longevity. The decreasing cost of batteries also makes the situation highly dynamic.

Europe is ahead of other parts of the world in developing regulation for batteries, as part of its broader efforts to develop a circular economy. It is exploring eco-design rules for batteries which would require the manufacturer to consider recycling and reuse during the design phase. Another lever might be to require the manufacturer to take back their product at the end of life. In the research and development community, there is much interest in life cycle assessment and the circular economy – for example, in relation to battery electric vehicles and hydrogen fuel cells. Better life cycle inventory data on materials and processes would help drive design improvements.

An industry is developing around the concept of second life: significant investments are going into battery recycling facilities. However, most manufacturers are currently prioritising performance and cost, rather than design for recycling. In the absence of regulations or incentives based on a clear understanding of the value of second life, it is challenging for manufacturers to develop a business case for reuse and recycling of batteries. Without regulation, it is unlikely that end-of-life costs will be included in products. Greater clarity is also needed on the costs and feasibility of battery recycling.

Environmental impact of scaling up new systems

It is vital that the environmental impacts of creating and operating the future energy system are understood in advance to avoid or mitigate major risks. The environmental impacts associated with the use of new low-carbon technologies must not exceed the reduction in environmental impact as fossil fuels are taken out of the energy system. Different mechanisms for environmental damage are understood, but the data does not yet exist to quantify risks for a future system operating at scale. Mining and extraction of materials is one aspect. It is vital that the transition does not lock us into a reliance on scarce materials which cannot be scaled up. There is much interest in developing technologies that use earth-abundant materials.

Hydrogen can easily leak during storage or transportation, which potentially be an economic factor, as well as a safety issue[18]. The impact on the nitrogen cycle of using ammonia at scale, and the creation of NO_x during ammonia production, are further concerns.

Safety

The issue of safety is important for new fuels such as hydrogen and ammonia. Vapour toxicity is the primary safety concern for ammonia, and flammability is a further issue. Ammonia is already stored and transported in large quantities throughout the world including the US, so its safety track record is of interest. In the past, a number of freight train derailments in the US have resulted in ammonia releases. The 'Jack Rabbit' research programme was initiated to investigate the toxicity of large releases of chlorine, and a future phase in the coming years will investigate ammonia. Research on the use of ammonia as a fuel in aviation, where safety is a primary concern, has considered three different ways to store ammonia to reduce its propensity to evaporate: as a liquid at its melting point (-77°C), as a slush (a mixture of solid and liquid) and as a solid. Military technologies, such as the use of foam in fuel tanks, also offer ways of improving safety. Technical solutions to reduce safety risks are likely to be feasible but costly.

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[18] BEIS, Hydrogen for heating: atmospheric impacts, Research Paper 2018: no. 21 Hydrogen_atmospheric_impact_report.pdf (publishing.service.gov.uk). See https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/760538/Hydrogen_atmospheric_impact_report.pdf (accessed 11 November 2021).

The explosive nature of hydrogen is a safety concern. The level of risk depends on the use case; for example, the risk of harm is greater if hydrogen is used in close proximity to people or in a confined space. The challenge is how to create the administrative controls so that it is used appropriately in different situations. It may be safer in a centralised application with higher levels of stewardship than a highly distributed system with lower fuel loads but a less sophisticated safety system. There is a question about the acceptable level of risk. Public acceptability of fuels such as hydrogen and ammonia could affect whether they can be adopted, especially if any incidents occur early on in their deployment.

The safety of lithium-ion batteries, either stored or in transport, is also an issue as some types pose a fire hazard.

Supply chains and markets

Energy storage technologies need a clear product definition in order to establish markets and build efficient and scalable supply chains. By accelerating product definition as early as possible in technology development, the market will be ready to support the growth in storage. A better understanding of the whole value chain would be beneficial: this should include value to the various end-users, such as risk mitigation and reliability, as well as upstream value to supply chains.

The value of energy storage depends on a range of factors including end-use, scale and geographical context, so a more granular understanding of the value of a product to different markets would be helpful. For example, a highly-decarbonised localised grid comprising micro-renewables, such as may emerge in the developing world, would have different energy storage requirements to a large national grid such as the GB grid. The increased complexity of the energy system resulting from cross-sectoral coupling makes it all the more important to understand how different sectors will work together and the relative value of different technology options, particularly as supply chains are emerging.

Existing industries such as the chemical industry already have established markets and supply chains for hydrogen and ammonia; there is potential to build on these to support growth. There is also already a market for storage in ancillary services, with potential to broaden this market to large-scale longer-term applications once technologies are further developed.

Heterogeneity in storage products will be needed to integrate renewables over different time scales and address the diverse needs of customers. Supply chains and markets rely on efficiencies of scale, but there is an inherent tension between diversity and scale. To help manage this, incentives and support mechanisms may be needed. Companies might be incentivised to invest in new technologies if they have good access to finance. Certification schemes such as an international ‘green stamp’ for ammonia would verify that it has been produced to zero carbon standards and help establish markets. Other mechanisms, such as a renewables international trading scheme or a carbon tax might help enable diverse markets and supply chains to develop.

It is not clear how much government intervention would be needed to create a market that meets consumer needs. In theory, the market will decide what opportunities are worth pursuing and the technology will diffuse into the market if it is good enough. However, there is a risk that the market will create solutions that do not meet broader societal objectives.

There may be lessons from the development of supply chains and markets for existing storage technologies, such as lithium-ion batteries or pumped hydro or fuels, that can be applied to emerging storage technologies. There are some similarities in the fertiliser market, where production is geared up to manufacture and store year-round but is only used once or twice a year. The hydrogen storage market may have similarities to the current natural gas storage market. There are also many differences: for example, many current battery applications require frequent and short-term use, rather than the infrequent and long-term uses for grid reliability.Storage technologies such as hydrogen will have many additional uses, including in plastic production or chemical reduction, or as a fuel or heat source. This will enable revenue stacking: the ability to derive value by serving multiple applications over the course of a day, month, or year.

Circular supply chains help manage both end-of-life considerations and raw material risks. The feasibility of developing circular supply chains depends on a number of factors such as equipment lifetime, recyclability and the value of the raw materials used in components relative to the cost of recovering them. Some technologies can be expected to last longer than others or are easier to recycle. A number of technologies use valuable elements, such as PEM cells which contain iridium and platinum. However, the wide range of equipment designs, for example types of battery construction, increases the costs of recycling relative to processing raw material.

New sources of raw materials are being sought and found for battery, electrolyser and catalyst components all the time, and there is a drive to towards using earth-abundant materials.

Technical opportunities and barriers

The challenge is to come up with energy storage options that are suitable for grid-scale applications, cost-competitive, ideally made from earth-abundant materials and are recyclable or have long lifetimes. However, there is little market pull for grid-scale storage at the current time which makes drawing through alternative technologies at scale a challenge.

A number of emerging battery technologies use alternative materials to avoid critical supply issues and reduce costs. For example, lithium iron phosphate batteries avoid the use of cobalt which has social and environmental issues associated with its mining. These batteries cannot achieve the same energy density as other chemistries, which is a limiting factor in transportation because of weight and volume constraints, but not for grid-scale applications. The use of manganese in batteries, which is hundreds of times more abundant on earth than lithium, is another option being explored. Flow batteries could become cost-competitive if abundant materials can be used for the cell. For example, ESS Inc. and Pacific North West National Laboratory are developing iron-based flow battery technologies. Liquid metal batteries, such as those being developed by Ambri[19] using technology developed at MIT, are a further cost-competitive option although they do not scale in the same way as flow batteries.

More ‘exotic’ storage technologies may be possible. For example, metallic iron could provide a thermo-chemical solution for long-duration storage. In theory, it is possible to build up iron reserves over many weeks from abundant sources of iron ore, and re-oxidise the iron to produce hydrogen when it is needed using a gasification process with steam. The challenge would be to produce hydrogen on demand at a sufficient rate and scale. However, iron ore is cheap, supply chains for the steel industry already exist and the technology offers a way of reusing scrap steel. The technology could also have wider benefits in helping to decarbonise the steel industry. Other chemistries involving non-stochiometric oxides such as zinc and zinc oxide, or tin and tin oxide, could be easier to manage than iron.

How does metallic iron storage compare with other forms of hydrogen generation and storage? If hydrogen is instead produced over time and stored underground in salt caverns, the limiting factors include the storage capacity and the efficiency of compressors used to compress hydrogen. Hydrogen produced using steam methane reformation can be part of the net-zero transition provided it is equipped with carbon capture and sequestration: the use of chemical looping is attractive as it separates hydrogen and carbon dioxide, producing a good quality carbon dioxide stream which is relatively easy to capture and use

Biofuels could be used for storage. In the US, corn ethanol is already produced in large quantities for use as a fuel in cars. Power plants running on biofuel exist both in the US (Schofield Generating Station in Hawaii) and the UK (Drax power station). Certain biofuels require chemical refinement if they are to be stored.

It is uncertain which technologies will become viable most quickly, although technologies with lower capital costs are most likely to win the race. It is also not clear how state-of-the-art technologies will compete with existing technologies. For example, could combustion turbines that run on ammonia be least risky as long-term storage solutions, if the technology can be demonstrated at scale and the risk of NO_x is mitigated? These could in theory be used alongside lithium-ion batteries and wind and solar power to meet the necessary attributes of the future system. Or will alternative technologies become competitive?

Policy issues

Sustained policies are needed to encourage sustained investment, regardless of the type of technology. Policies must evolve to support the transition to the future system and go well beyond financial support for research and development. It may be that levers used in the past, such as the production tax credit used in the US to incentivise wind energy deployment, are not suitable for energy storage if they reward the production of energy but not the provision of critical grid services. A broad incentive system for low-carbon energy may be preferable: one that allows the market to find the lowest-cost solution, rather than mandating a particular pathway or technology. However, there are examples of more prescriptive approaches; for example, New York has mandated 9 GW of offshore wind as part of its climate protection policy act[20].

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19. Amri Technology. See http://www.ambri.com/technology/ (accessed 11 November 2021).
20. New York Climate Leadership and Community Protection Act (CLCPA) 2018.

Greater certainty is needed up front about the attributes of the low-carbon energy system and how energy storage will operate in that system in the short- and long-term. The modelling community must provide clarity to policymakers about the required storage capacities and durations and the lowest cost options. Utilities need to be clear about the role of energy storage. The challenge of incentivising the development and deployment of energy storage, while natural gas remains in the system as a more competitive option, must be born in mind.

There are challenges for energy system modelling: it is hard to characterise all the different technologies and fuels across the system, especially as those characteristics are changing rapidly. Uncertainty exists not only about the technical and economic performance of the different storage options, but also their role in a high-renewables grid alongside other buffering mechanisms, such as cross-sector coupling, load shifting by demand management or oversupply and curtailment. Storage technologies also have value for their role in providing grid services and in decarbonising other sectors. Better data on various fuel and storage pathways would be helpful. Inter-model comparisons, to critically assess differences in models, would help improve model robustness. Clarity about modelling uncertainty, and the consequences of that uncertainty on decision-making, is vital. Given current uncertainties, it makes sense to develop a portfolio of options based around future scenarios that might include low-regret and theoretically optimised solutions.

Government has a role in investing in high-risk, high-reward storage technology options to move them to higher technology readiness levels so they can be adopted into the marketplace, should they be needed. Support at laboratory scale, pilot scale and then pre-commercial scale would help de-risk technologies before they are launched commercially. There is value in growing an innovation ecosystem that comprises academic institutions, industry and other relevant stakeholders. Given the technological uncertainty, the timescale to develop new energy infrastructure over the coming decades is challenging, requiring demonstration and scaling up, a market response, deployment at scale and integration. Demonstration of energy storage technologies should ideally be carried out by 2030, after which deployment can begin to replace existing assets.

A road mapping process might characterise different categories of energy storage technologies according to their attributes, and the different levels of performance and cost they must reach in order to be viable within the system. A number of options within each category would then ideally be developed, comprising both breakthrough technologies and high TRL technologies that are closer to commercialisation.

The operation of capital markets and energy markets in the short- and long-term is an important consideration. Markets are likely to evolve over time as the amount of renewable energy in the system increases with time. The dynamics of the market structures will need to be considered alongside the progress of technology development. Policymakers will have a role in ensuring the appropriate market mechanisms are in place to incentivise deployment of energy storage technologies.

A central challenge is the low utilisation of energy storage technologies that are needed to ensure the system meets its reliability requirements. Although the cost per watt is similar for renewable generation and energy storage, the difference in utilisation means that storage dominates economic viability. There may be opportunities to maximise asset utilisation through developing uses beyond the grid, in other sectors of the economy. Alternatively, it may be that an entity will need to own uneconomic assets to ensure reliability. The role of independent system operators may need to be extended to include energy storage.

6. Opportunities for international collaboration

A number of areas for international collaboration emerged during the course of the discussions. It was felt that collaboration was most feasible on pre-competitive areas of research, which might be about methodology as much as technology.

Energy system modelling
comparing approaches to modelling and sharing input data that characterises the different technologies and fuels across the system. Collaboration on ways of modelling the system to demonstrate the value of different storage options in the short- and long-term and pathways. Whole-system approaches. Collaboration on using energy systems modelling in policy development.

Lifetime prediction and performance
collaboration on understanding the relationship between duty cycle and lifetime, and the ability to predict lifetime prior to deployment. Impact of chemistries and materials on performance of different technologies. Protocols for testing, including accelerated testing.

Recycling
collaboration on developing ways to recycle cost-effectively and on design for recycling or reuse. Safe and automated ways to recycle. Policy to incentivise recycling.

Minimising environmental impact
methodologies and data for life cycle assessment; understanding and quantifying the impact of the future energy system on global warming and other environmental impacts.

Low technology readiness level (TRL) technologies for long-term storage
thermal energy storage; thermal production of hydrogen: stochiometric (e.g. iron) and non-stoichiometric oxides; liquid organic hydrides; ammonia and hydrogen; bioethanol; hybrid technologies; CCS with existing fuels; flow batteries.

Repurposing existing assets
use of alternative fuels in existing assets. Technologies for low- and middle-income countries: e.g. small batteries and converted internal combustion engine technologies that run on ammonia.

7. Concluding thoughts

Suitable technologies exist to create a net-zero electricity system so long as the political will and capital are present. A central question is how best to optimise this future system in response to national, regional and local contexts.

In the case of a high-renewables grid, energy storage could play a vital role in delivering dispatchable power during times of solar and wind drought and in providing grid services to maintain grid reliability. A portfolio of energy storage technologies will be needed with a range of performance characteristics. While wind and solar power costs will decrease over the coming years, the costs of long-duration energy storage are likely to pose the greatest challenge to economic viability unless efforts to reduce costs are successful. Further technological developments will help to reduce costs and increase the performance of energy storage, although uncertainty remains about what cost reductions are possible and what future system requirements will be.

A wide range of energy storage technologies with different durations are emerging. There is also potential to repurpose existing technologies such as gas turbines to run on more sustainable fuels such as hydrogen or ammonia. The science and engineering communities have an important role in developing and comparing technology options and investigating how different options might best work together in a future system. It is important that those findings are communicated clearly and consistently to policymakers.

There is a risk of technology partisanship among policymakers or researchers that can lead to sub-optimal systems. Until there is greater clarity about the optimal system, a portfolio of plausible energy storage technology options should be developed, avoiding pushing individual technologies before their time. A consistent approach to funding will be needed over the coming decade to ensure technology deployment happens at sufficient pace to meet net-zero targets. Technology development must be directed with future end-uses and system requirements in mind, including the potential for cross-sectoral coupling. More broadly, options for dispatchable power beyond energy storage should not be ruled out, or indeed alternatives to the all-renewables grid such as CCS combined with gas cycle turbines or nuclear energy using small modular reactors, for example.

Market evolution must be considered alongside technology development. There is a risk that the market will not deliver the optimal solution without some form of government intervention or restructuring. The challenge will be to incentivise investment in the deployment of long-duration storage options while natural gas, a much less costly form of storage, remains in the system, and to transition to a grid that delivers the widest societal and economic benefits.

Acknowledgements

The Royal Society and the National Academy of Sciences would like to thank all those who contributed to the development of this project.

Co-Chairs

Professor Steve Koonin, Professor of Information, Operations and Management Sciences
Leonard N Stern School of Business, New York.

Sir Chris Llewellyn Smith FRS, Emeritus Professor of Physics, University of Oxford.

Committee members

Terry Boston, President and CEO Terry Boston LLC.

Professor Nigel Brandon FREng FRS, Dean of the Faculty of Engineering, Imperial College London.

Professor Clare Grey FRS, Geoffrey Moorhouse Gibson Professor of Chemistry, Department of Chemistry, University of Cambridge.

Patricia Hoffman, Principal Deputy Assistant Secretary, Office of Electricity, U.S. Department of Energy.

Professor Matthew Davidson, Director of the Centre for Sustainable Chemical Technologies, University of Bath.

Professor Nathan Lewis, Professor of Chemistry, Division of Chemistry and Chemical Engineering, California Institute of Technology.

Staff

Frances Bird, the Royal Society

Paul Davies, the Royal Society

Ken Fulton, National Academy of Sciences

James Musisi, the Royal Society

Elizabeth Surkovic, the Royal Society

Rapporteur

Dr Philippa Westbury

Forum programme

Day 1 (17 March 2021)

WELCOME PLENARY

Outline of the US/UK electricity systems and the current research and demonstration programmes to decarbonise them

Welcome

Chris Llewellyn Smith, event co-chair,
Steve Koonin, event co-chair

Pre-recorded lectures

Dermot Nolan *UK and US electricity systems: the basics*
Patricia Hoffman *Electrical storage in support of the grid*
Lynn Gladden *UKRI's contribution to decarbonising the energy system*
Nate Lewis *Reliable decarbonised future US electricity systems*

Panel Members

Lucy Martin, Engineering and Physical Sciences Research Council
Patricia Hoffman, US Department of Energy
Nate Lewis, California Institute of Technology
Dermot Nolan, Fingleton

PLENARY 1

Managing a high renewables grid

Chair: Steve Koonin, National Academy of Sciences

Pre-recorded lectures

Patrick Hogan *The Evolving Grid*
Tony Roulstone *Assessing the need for future energy storage*

Panel Members

Ana Barillas, Aurora Energy
Joseph DeCarolis, NC State University
Paul Denholm, National Renewable Energy Laboratory
Patrick Hogan, Utility Technology Solutions
Tony Roulstone, University of Cambridge
Marcus Stewart, National Grid

PLENARY 2

Storage Technologies I

Batteries and electrochemical storage

Chair: Clare Grey, University of Cambridge

Pre-recorded lectures

Peter Bruce *Li and Na-ion batteries for grid scale energy storage*
Venkat Srinivasan *Batteries for a zero-carbon grid: present status and opportunities*

Panel Members

Nigel Brandon, Imperial College
Peter Bruce, Faraday Institute & University of Oxford
Steve Davis, University of California, Irvine
Venkat Srinivasan, Argonne Collaborative Center for Energy Storage Science

Alternative energy storage methods

Chair: Steve Koonin, National Academy of Sciences

Pre-recorded lectures

Yulong Ding *Thermal Energy Storage for a net-zero future*
Robert Schainker *Compressed Air Energy Storage (CAES): Executive overview*

Panel Members:

Yulong Ding, University of Birmingham
Phil Eames, Loughborough University
James Klausner, Michigan State University
Robert Schainker, Electric Power Research Institute

Day 2 (18 March 2021)

PLENARY SESSION 3
Storage technologies II

Hydrogen & Ammonia Production

Chair: Bill David, University of Oxford

Pre-recorded lectures

Katherine Ayers *Cost reduction of large scale electrolysis for energy applications*

Trevor Brown *Ammonia: a pathway to market*

Panel Members

Katherine Ayers, Nel Hydrogen US
Trevor Brown, Ammonia Energy Association
Paul Chirik, Princeton University
Deborah Jones, University of Montpellier
Thomas Mallouk, University of Pennsylvania
Marcus Newborough, ITM Power

Hydrogen & Ammonia Utilisation

Pre-recorded lectures

Jeffrey Goldmeer *Decarbonising our energy ecosystem with gas turbines*

Mark Selby *Future fuels and fuel cells*

Panel Members

Sally Benson, Stanford University
Jeffrey Goldmeer, General Electric Gas Power
Anthony McDaniel, Sandia National Laboratories
Jane Patterson, Ricardo UK
Mark Selby, Ceres Power
Rob Stevens, Yara

BREAK OUT SESSIONS

Break out on cross cutting issues re techs discussed in earlier sessions

Breakout co-chairs

Alan Greenshields, Innolith
Marcelle McManus, University of Bath
Elizabeth Endler, Shell
Kory Hedman,
Power Systems Engineering Research Center
Terry Boston, PJM Interconnection
Cameron Hepburn, University of Oxford
Judith Judson, National Grid
Mike Muskett, Technical Consultant

BREAKOUT FEEDBACK SESSION

Feedback session

Chair: M Granger Morgan, Carnegie Mellon University

PLENARY SESSION 4
Closing discussion

Reflections from meeting

Steve Koonin, event co-chair
Chris Llewellyn Smith FRS, event co-chair

Concluding remarks

Paul Monks, UK Chief Scientific Adviser for the Department for Business, Energy & Industrial Strategy

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For further information
The Royal Society
6 – 9 Carlton House Terrace
London SW1Y 5AG

T +44 20 7451 2500
E science.policy@royalsociety.org
W royalsociety.org

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Issued: September 2022 DES7752