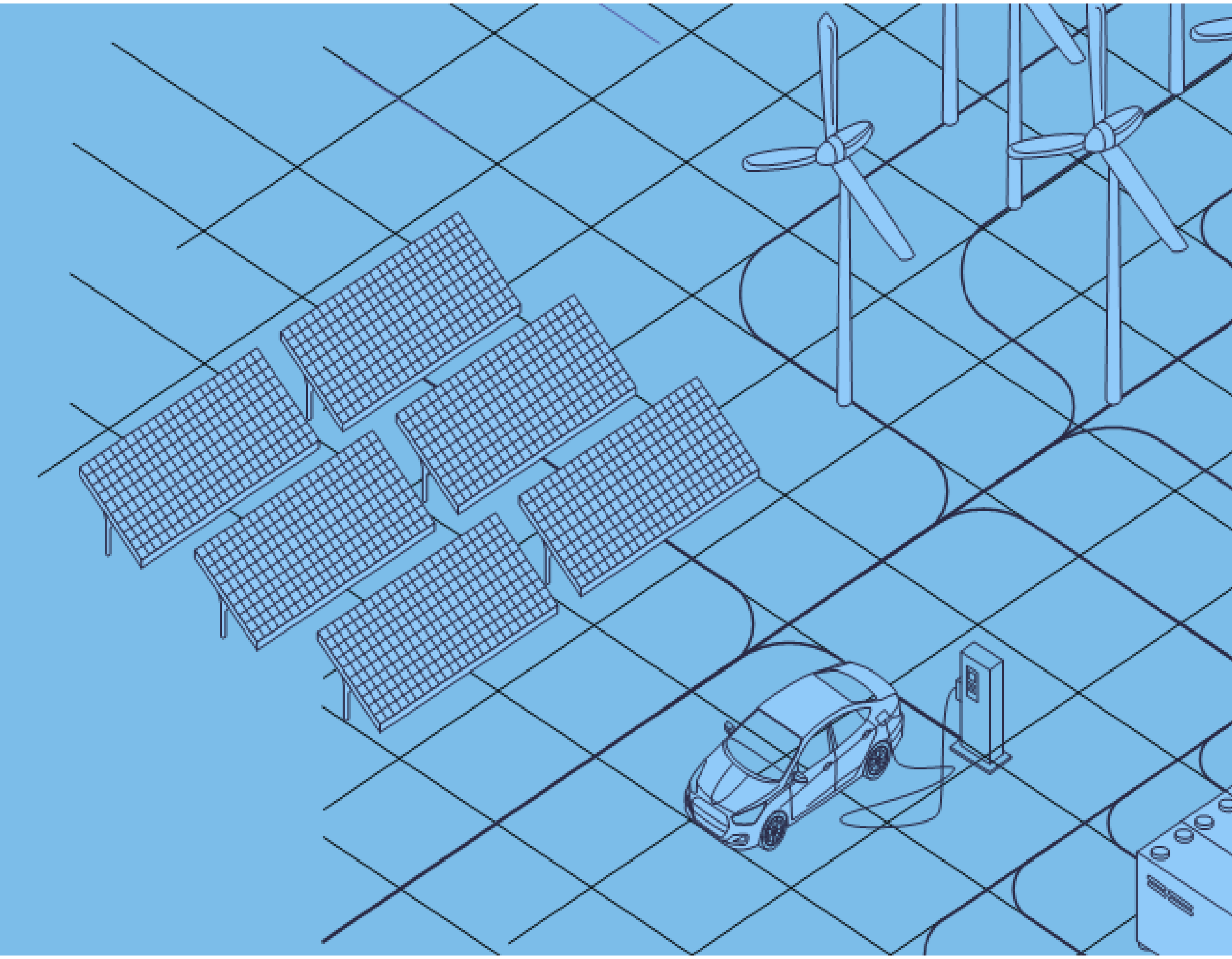

Market and Technology Assessment of Grid-Scale Energy Storage required to Deliver Net Zero and the Implications for Battery Research in the UK

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Table of Contents

Table of Figures

Table of Tables

Executive Summary

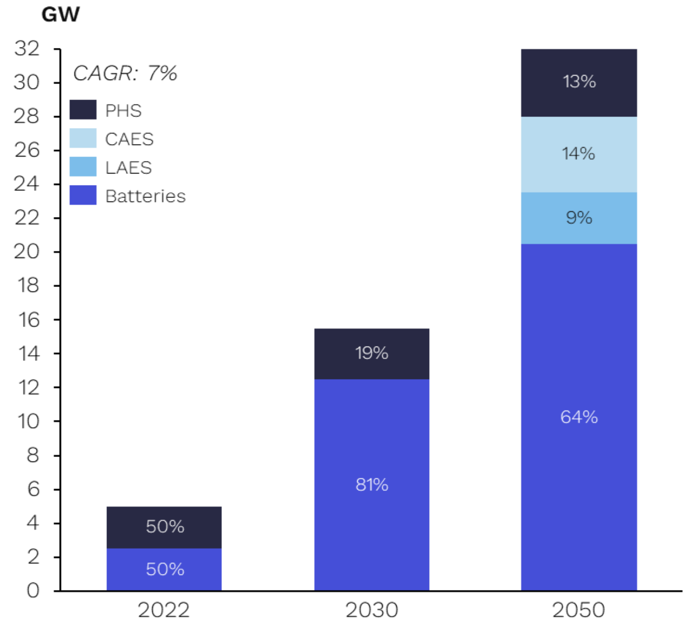
The UK is currently undergoing a significant energy transition, driven by a commitment to decarbonise industries, the power supply and deliver Net Zero. Under a future energy system dominated by renewables, the supply of energy will increasingly be determined by the strength of wind and solar.

However, this intermittent generation of electricity will pose critical challenges for ensuring a sustainable and flexible UK energy grid. Unlike other forms of energy, electricity cannot be stored directly and requires conversion into alternative energy forms for effective storage. Several technologies exist to convert electricity into energy storage systems (ESS), including pumped hydro, compressed air storage, liquid air energy storage, and batteries, each offering different durations of storage. The selection of stationary storage technologies with varying durations depends on the specific requirements and characteristics of the energy system.

The study assesses the scale, type, and technical characteristics of the grid-scale stationary energy storage required for Net Zero. It identifies and assesses the existing and future energy storage technologies most suitable for delivering the UK's requirements and outlines the implications for scientific research in the UK. The study focuses on electrochemical storage technologies such as lithium-ion batteries, and future technologies, such as sodium-ion and redox flow batteries, which have the potential to be commercialised and come to market in the next decade or so.

Battery energy storage systems (BESS) are expected to dominate the flexible ESS market, capturing 81% and 64% of installed capacity by 2030 and 2050 respectively (Figure 1). With 2GW of lithium-ion BESS capacity already installed, the industry is anticipated to experience an average 7% increase in ESS capacity each year to 2035, reaching over 12GW of capacity by 2030 and 21GW by 2050. This growth presents opportunities for innovation, improved energy security, resilience, and affordability.

Figure 1. UK ESS current and projected installed capacity until 2050

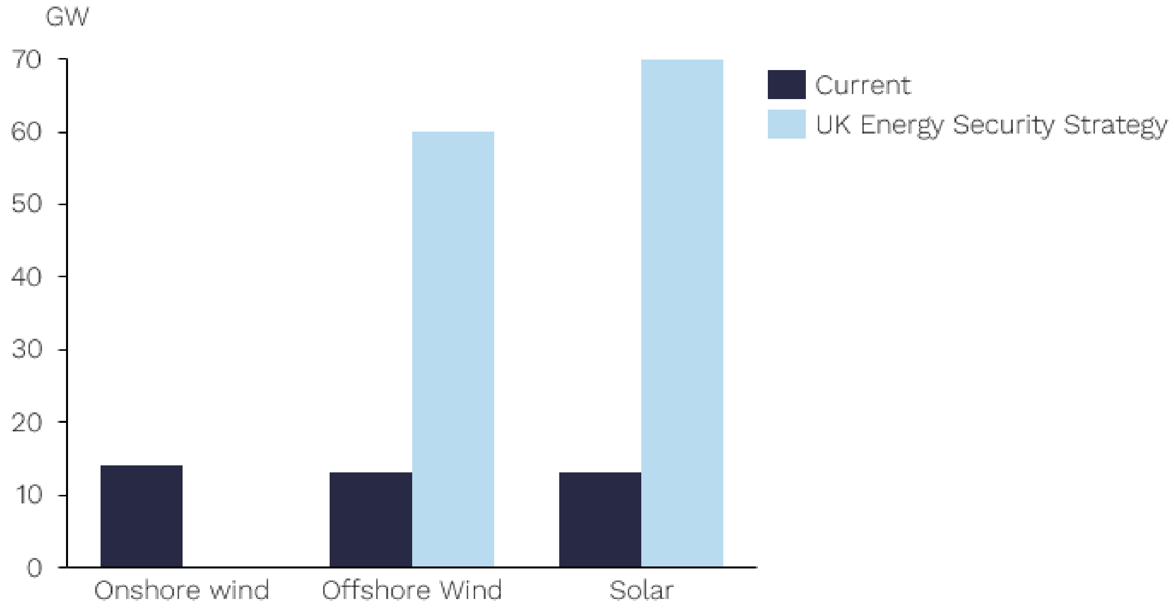


Source [ESO Future Energy Scenarios, System Transformation Scenario 2022](https://www.nationalgrideso.com).

ESS and BESS market assessment

The UK has set ambitious targets for renewable energy supply by 2035, aiming to quadruple offshore wind capacity by 2030 and increase solar capacity five-fold by 2035 (Figure 2). Infrastructure development needs to surpass previous renewable energy deployments to meet these targets.

Figure 2. UK Government's renewable capacity targets by 2035



Source [*BEIS (2022) British Energy Security Strategy*]().

To effectively facilitate the deployment of renewables and the energy transition, the following key factors need to be considered.

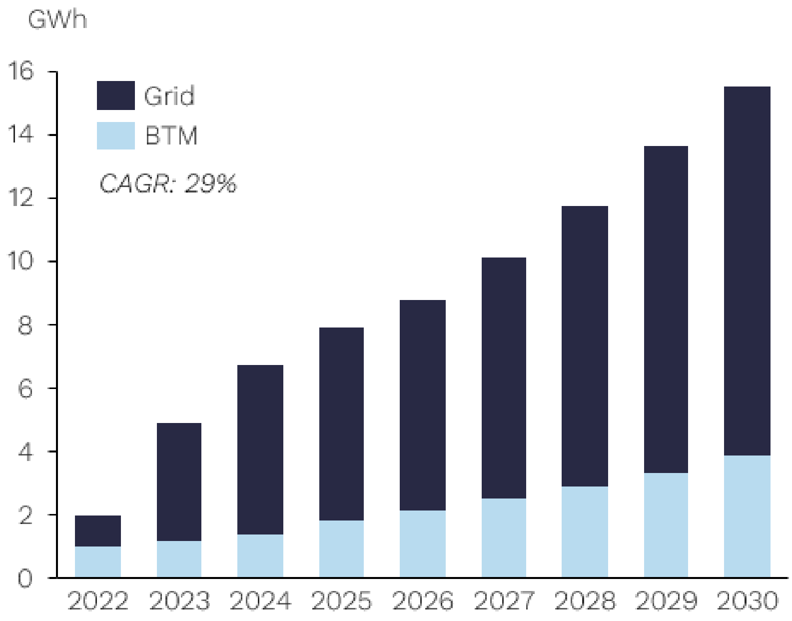
The importance of electrical grid flexibility is crucial due to the significant variations in electricity demand. Flexibility is needed from the generation, transmission and distribution parts of the power system, as well as from end users. Ten key applications (Table 4) have been developed across the power system to manage flexibility, such as slow-to-fast discharge and medium-to-high power, to address different scenarios such as ramp and voltage support, off-peak storage, frequency regulation, stability, wind power gradient reduction, power-oscillation damping, and rapid demand support.

ESS can help resolve the UK's grid flexibility concerns stemming from reliance on natural gas for peaking capacity. However, Pumped Hydro Storage (PHS) and Battery Energy Storage Systems (BESS) are expected to have a more significant role in the future. BESS deployment in particular is expected to increase significantly, and BESS will dominate the energy storage landscape by 2050. Long-duration storage needs, spanning weekly, monthly, and even seasonal durations, are expected to be met by a combination of green hydrogen and PHS. Lithium-based batteries are anticipated to be the primary technology for stationary energy storage, driven by economies of scale and the growth of Electric Vehicles (EV). Although PHS and Compressed-Air Energy Storage (CAES) have limitations such as long lead times and geographical restrictions, CAES presents an opportunity for cost reduction, and Liquid-Air Energy Storage (LAES) offers broader deployment possibilities.

Grid flexibility applications influence the suitability of ESS technology. PHS offers high energy capacity and long-duration storage capabilities, making it ideal for large-scale energy storage and grid balancing over longer periods. CAES and LAES also offer high energy capacity but have shorter storage durations and are more suitable for peaking power and grid stability during short-duration demand spikes. Battery technologies offer lower energy capacity but can deliver power quickly and efficiently, making them suitable for short-duration energy storage and ancillary services. The cost of energy storage technologies depends on various factors including capacity, project size, and environmental conditions. PHS and CAES are generally more cost-effective for larger-scale projects, while battery technologies are more suitable for smaller-scale applications. LAES is a relatively new technology that has shown promising results, but its capital costs are currently higher than those of other energy storage technologies.

BESS grid-scale will form the backbone of the UK's flexibility landscape, with 29% CAGR growth until 2030 anticipated. Annual installed BESS capacity is expected to surpass 15 GWh by 2030 (Figure 3). Grid-scale BESS accounted for more than 50% of installed capacity in 2022, increasing to 75% by 2030, driven primarily by renewable paired applications to support the UK's commitment to net zero, especially in offshore wind projects. Behind-the-Meter (BTM) applications are projected to make up the remaining 25% of the BESS market in 2030.

Figure 3. UK BESS annual installed capacity in GWh by 2030

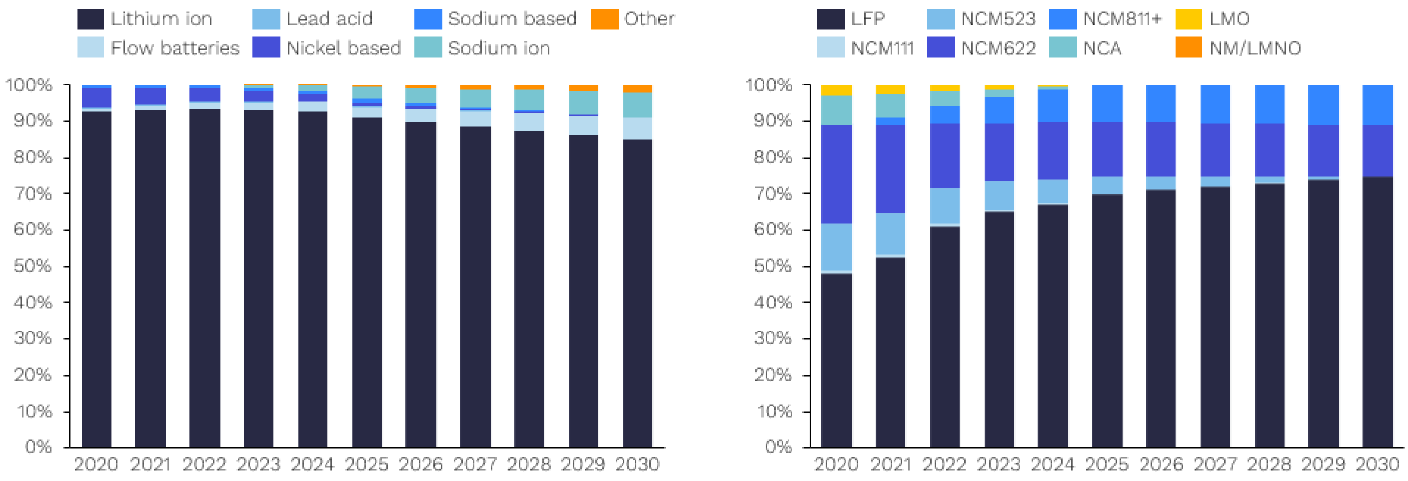


Source Rho Motion

While this report focuses on grid-scale applications, it is important to note that grid-scale and BTM storage are not mutually exclusive. Grid-scale storage can be used in a behind-the-meter manner, enabling larger renewable paired storage systems to store and utilise on-site generated energy, improving commercial viability and reducing costs. In the BTM market, solar-paired installations will play a crucial role, comprising nearly half of the market share by 2025.

Lithium batteries and particularly LFP chemistries are poised to dominate the UK BESS landscape. As EV battery technology advances, it creates opportunities for BESS to leverage shared technologies, benefit from economies of scale, and access a robust supply chain. Lithium-ion batteries are expected to represent around 90% of grid-scale installations and 80% when combined with BTM storage. The use of lithium-iron-phosphate (LFP) battery chemistry, in particular, is expected to dominate due to their cost-effectiveness and improved cyclability, with the market share rising from about 60% in 2022 to over 70% by 2030 (RHS Figure 4). However, alternative BESS technologies such as redox flow batteries and sodium-ion batteries are expected to gain traction. Flow batteries are projected to capture 6% of the total BESS market in the UK by 2040, while sodium-ion batteries are expected to rise from 1% in 2024 to over 7% by 2040 (LHS Figure 4). These technologies offer unique advantages and are being developed by companies such as Invinity Energy Systems, Faradion, and AceOn. Additionally, sodium-ion batteries exhibit a strong capability to retain energy in colder temperatures, which is relevant for the northern parts of the UK.

Figure 4. UK BESS technology outlook (LHS) and Li-ion chemistry split (RHS)



Source Rho Motion

Battery technology assessment

The choice of BESS technology to support decarbonisation and help manage the increasing deployment of renewable generation depends on specific grid applications and the following six key performance indicators:

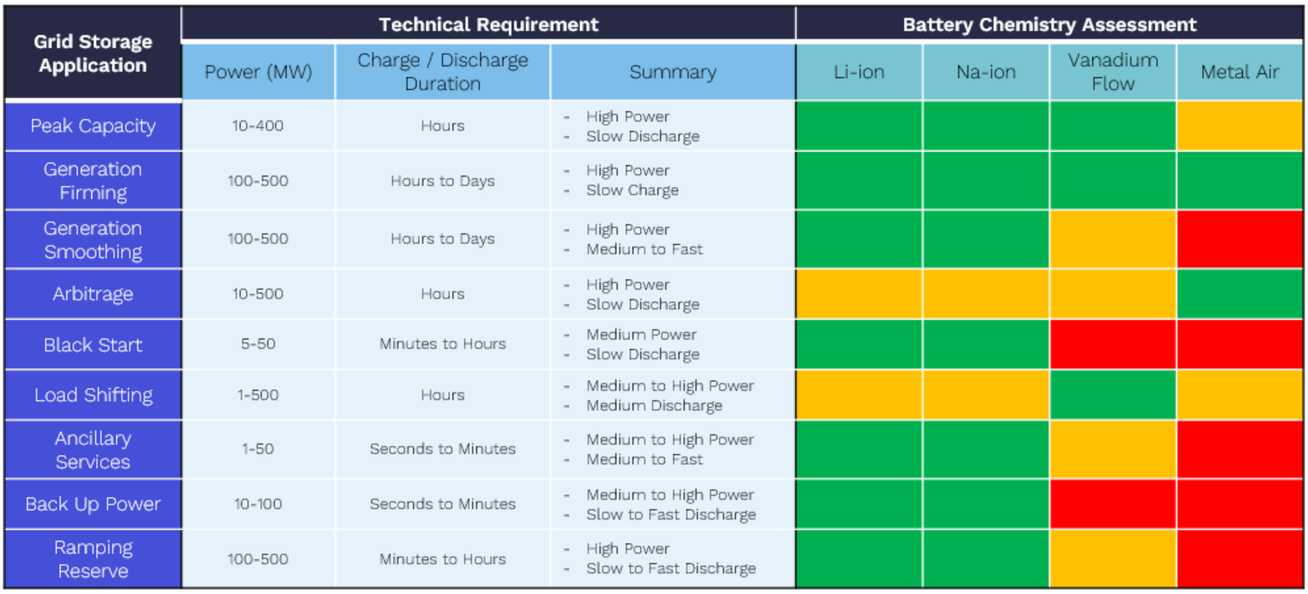
1. **Grid flexibility**
2. **Charge / discharge duration**
3. **Storage duration**
4. **Power**
5. **Energy density**
6. **Safety**

Some of the key technology findings and suitability (Table 1) are summarised below:

The broadest range of grid flexibility solutions is offered by lithium and sodium-ion batteries due to high-energy and power capabilities, compact size, and fast response. Lithium and sodium-ion batteries are well-suited for applications where immediate access to stored energy is essential, such as backup power. Vanadium flow batteries are particularly suitable for generation firming, generation smoothing and load shifting applications, offering high power and longer duration charge/discharge cycles. They excel in providing consistent power over extended periods, contributing to efficient energy management and grid stability. Metal-air batteries are best suited for backup power applications as they are capable of delivering sustained power. However, their limited cycle life makes them less suitable for applications requiring frequent charge and discharge cycles. As a result, they are expected to not be commonly used for peak capacity, generation firming, generation smoothing, arbitrage, load shifting, or ancillary services.

Discharge and storage duration are key indicators for the amount of energy stored and released. Discharge duration is the length of time that stored energy can be continuously discharged from a BESS system at its power capacity, while storage duration relates to the ability of different technologies to retain a charge over time, known as self-discharge. Lithium-ion and sodium-ion batteries demonstrate relatively short self-discharge rates, typically losing around 5% of their charge within the first 24 hours and experiencing monthly self-discharge rates ranging from 0.5% to 3%. These technologies may not be optimal for multi-day and extended storage durations. In contrast, redox flow batteries offer promising capabilities for ESS lasting from hours to days, and potentially even months in seasonal storage applications. The distinct design of redox flow batteries, with separate electrolyte tanks, allows for a self-discharge rate close to 0%. Additionally, certain non-aqueous metal-air batteries show potential for minimizing self-discharge. Technologies with longer discharge durations and minimal self-discharge rates are better suited for applications requiring multi-day or extended energy storage.

Table 1. BESS suitability matrix, including technical and application



Grid Storage Application	Technical Requirement			Battery Chemistry Assessment			
	Power (MW)	Charge / Discharge Duration	Summary	Li-ion	Na-ion	Vanadium Flow	Metal Air
Peak Capacity	10-400	Hours	- High Power - Slow Discharge	🟩	🟩	🟩	🟨
Generation Firming	100-500	Hours to Days	- High Power - Slow Charge	🟩	🟩	🟩	🟩
Generation Smoothing	100-500	Hours to Days	- High Power - Medium to Fast	🟩	🟩	🟨	🟥
Arbitrage	10-500	Hours	- High Power - Slow Discharge	🟨	🟨	🟨	🟩
Black Start	5-50	Minutes to Hours	- Medium Power - Slow Discharge	🟩	🟩	🟥	🟥
Load Shifting	1-500	Hours	- Medium to High Power - Medium Discharge	🟨	🟨	🟩	🟨
Ancillary Services	1-50	Seconds to Minutes	- Medium to High Power - Medium to Fast	🟩	🟩	🟨	🟥
Back Up Power	10-100	Seconds to Minutes	- Medium to High Power - Slow to Fast Discharge	🟩	🟩	🟥	🟥
Ramping Reserve	100-500	Minutes to Hours	- High Power - Slow to Fast Discharge	🟩	🟩	🟨	🟥

🟩 Well suited 🟨 Plausible 🟥 Unsuitable

Source Renewable and Sustainable Energy Reviews (Kebebe, Kalogiannis, Mierlos).

Power is a key indicator for rapid response applications. Lithium-ion and sodium-ion batteries exhibit high power capabilities, making them well-suited for various applications such as load shifting and arbitrage. Vanadium flow batteries, while offering longer discharge durations, have relatively lower power capabilities and are not ideal for backup power applications. Alternative anode materials such as lithium-titanate oxide batteries (LTO) and niobium-based materials show promise for higher power densities. Sodium-ion batteries demonstrate superior power performance due to their greater conductivity. Flow batteries provide separate control of power and energy storage capacity, offering flexibility without compromising energy density. Metal-air chemistries, such as iron-air systems, may excel in long-duration applications but are not suitable for fast response requirements.

Energy density is a key indicator for assessing application size and weight. While gravimetric energy density is less critical for ESS, volumetric energy density is crucial for space-efficient installations, particularly when paired with renewable energy sources like solar panels. NMC offers high energy density but sacrifices thermal stability and cycle life, making it less suitable for BESS. LFP provides a safer and more durable alternative with lower energy density, making it favourable for BESS developers. Battery cell technology advancements in the EV space have a positive impact on ESS, with innovations primarily focused on the anode and electrolyte. Graphite, the dominant anode material, offers moderate fast-charging capabilities suitable for both EV and grid storage. Lithium titanate oxide (LTO) has lower energy density but improves charging capability and lifetime, making it well-suited for grid flexibility applications. Silicon shows promise with its potential for higher energy density, but challenges such as swelling during charging and poor conductivity need to be addressed. Metal-air technologies are being developed to utilize pure metal anode materials like lithium metal, offering the potential for higher energy densities. However, current commercial Metal-air technologies have relatively low energy densities.

Safety is a key indicator for ensuring the protection of personnel, equipment, and the environment. Several factors contribute to battery safety, including structural stability, operational temperature range, and susceptibility to thermal runaway. LFP batteries are inherently safer than NMC batteries. LFP has a higher ignition temperature, releases fewer gases, and generates less heat in case of battery malfunction, reducing the risk of fire. The enhanced safety of LFP allows for higher efficiency at the pack level, reducing the need for extensive thermal management. This results in space and weight savings, contributing to improved energy density. Sodium-ion batteries offer increased stability and safety compared to lithium-ion batteries. Sodium-ion cells can be stored in a fully discharged state, making their storage and transportation easier. Sodium-ion batteries also exhibit a slower heating rate during thermal runaway, allowing more time for heat dissipation and reducing the impact on surrounding cells in the battery pack. Redox flow batteries are considered inherently safer than lithium-ion batteries, as they have a lower risk of failure or short-circuit, reducing the likelihood of fire incidents. However, safety considerations for redox flow batteries include electrolyte leakage and the formation of gases from side reactions, which depend on the specific chemistry of the electrolyte used. Metal-air batteries, such as those using non-flammable aqueous electrolytes like Potassium Hydroxide (KOH), are also intrinsically safer than lithium-ion batteries.

Battery cost assessment

A comprehensive assessment of BESS application suitability should not only consider battery performance but also cost competitiveness, through an evaluation of key cost drivers, potential barriers, manufacturer incentives, and overall commercial viability. The following cost insights were identified.

Cost competitiveness is a challenge for vanadium flow batteries. Redox flow batteries, including zinc-bromine, vanadium, and iron chemistries, offer advantages such as long duration and extended cycle life, making them suitable for base load grid applications. However, their cost competitiveness remains a challenge compared to lithium-ion and sodium-ion batteries, with current prices ranging from US$200-400/kWh. Vanadium flow batteries have seen significant deployment, while zinc-bromine flow batteries are still in early-stage trials. The cost of vanadium and the cycle life issues associated with zinc chemistries pose potential challenges. To address these challenges, investments in advanced membrane materials and stable solid electrodes are needed. Despite the cost implications, redox flow batteries hold promise for long-duration grid applications.

Single electrode metal-air batteries offer advantageous cost savings. The use of pure metal anodes allows for higher specific capacity and energy density. Various metals, including lithium, sodium, zinc, aluminium, and iron, have been explored for Metal-air configurations. However, current metal-air technologies face challenges in achieving reversibility, limiting the number of cycles before the anodes require replacement. Metal-air batteries with single electrodes offer potential cost savings due to the use of pure metal anodes, enabling higher specific capacity and energy density. Various metals, including lithium, sodium, zinc, aluminium, and iron, have been explored for metal-air configurations. However, current metal-air technologies encounter challenges in achieving reversibility, limiting the number of cycles before anode replacement is needed. One notable advantage of certain metal-air batteries is the use of a single electrode, which can contribute to cost savings. This becomes particularly attractive as the lithium-ion supply chain face increasing pressure from the growing EV market, underscoring the importance of utilizing more cost-effective and abundant materials for energy storage systems.

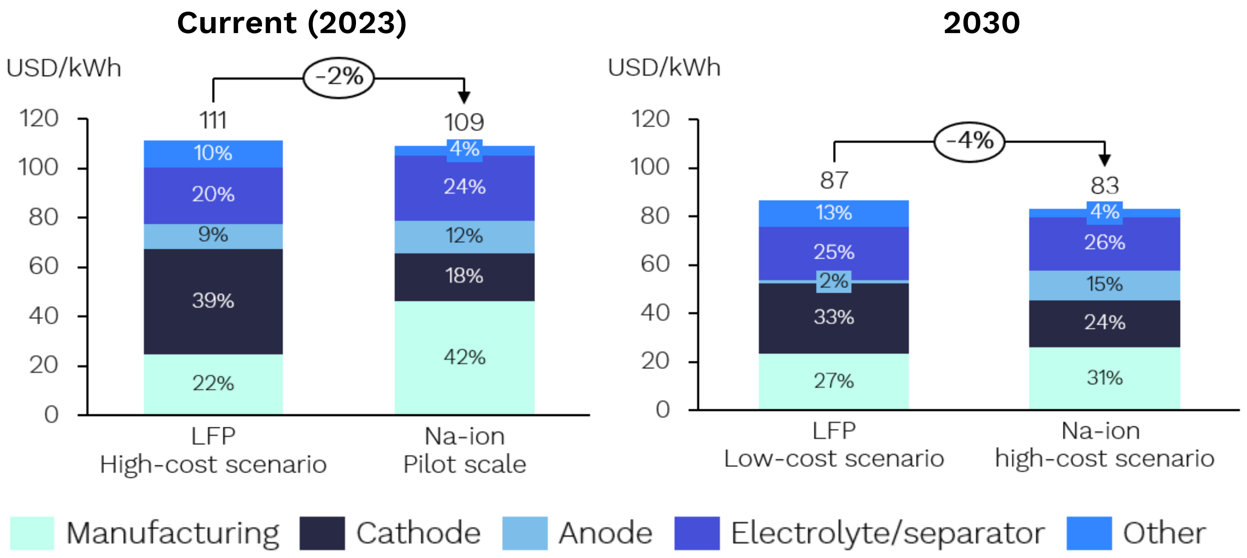
Lithium-ion cathode active materials are the main cost contributors. Cost reductions of 22% for NMC811 and 18% for LFP are projected by 2030 due to a mid-term market balance for key battery-grade materials. However, battery cell costs increased in 2022 due to rising metal prices, primarily lithium carbonate and hydroxide. The reasons for these cost increases include short-term pricing mechanisms, geopolitical factors, the Covid-19 pandemic, and supply bottlenecks. In the long-term, raw material pricing is expected to be driven by supply-demand balances and incentivized pricing for metal suppliers, leading to stable prices. The analysis also highlights that NMC811 tends to be more expensive than LFP in terms of cost per kWh, primarily due to higher Cathode Active Materials (CAM) costs. However, LFP manufacturing is relatively more expensive due to current collector foils and polymeric separators. The price volatility of battery-grade materials is expected to continue in the short-term, while the market is expected to be more predictable in the long-term.

Silicon anode is a possible pathway to cost optimisation. Silicon anode technology has the potential to significantly reduce costs in lithium-ion cells compared to traditional graphite anodes. Tesla and other companies are exploring the use of silicon nanowires and structured silicon in graphite anodes to achieve cost optimization and improve cell efficiency. Rho Motion modelled the cost pathway for lithium-ion cells using various evolutions of silicon anode up to 2030. The results show that the current anode active material accounts for around 7% to 9% of total cell cost in NMC811 and LFP chemistries, which is expected to reduce to about 2% by 2030 with the adoption of optimized micro-silicon at scale. Manufacturing-led innovations, supply chain synergies, and the conversion of metallurgical-grade silicon into silicon nanoparticles, can lead to cost reductions from around US$12/kWh to a potential cost floor of US$2-4/kWh. Additionally, the adoption of pre-lithiation and dry electrode processing shows promise in maintaining cell efficiency and reducing processing steps. However, further development and scale-up is required for these approaches.

Sodium-ion could be a cost competitive alternative to LFP. Sodium-ion batteries could achieve up to 30% lower material costs compared to LFP. Companies such as CATL, HiNa Technology, Natron Energy, and Faradion are actively developing sodium-ion technologies, with CATL's first-generation sodium-ion batteries for BESS applications being seen as a significant breakthrough in the industry. Sodium-ion batteries offer manageable supply chains and the ability to utilize existing production lines from lithium-ion battery manufacturing, leading to potential cost savings through amortized equipment costs. Rho Motion's sodium-ion cost model reveals a clear pathway to cost optimization. In the 2025-2030 period, marginal cost efficiencies are achieved through active materials and optimized manufacturing at scale. In the post-2030 period, further cost reductions are expected through cheaper anode and electrolyte materials. The modelling also includes sodium-ion "power" cells with reported energy density similar to Natron's, indicating a higher total cell cost compared to the baseline model. However, with an optimized example, the total cell cost becomes comparable to the baseline, making sodium-ion power cells a viable cost and performance alternative. Notably, Natron reports impressive performance characteristics, including an eight-minute charge time, a minimum service life of five years, and 35,000 cycles without capacity loss.

LFP and sodium-ion cost differences are driven by the bill of materials. The overall cost advantage of sodium-ion over LFP ranges from around 2% to 4% (between 2023 and 2030) according to optimization scenarios (Figure 5). The cost difference is primarily driven by lower active material costs in sodium-ion and the use of aluminium foil instead of expensive copper in both the anode and cathode. However, manufacturing costs in sodium-ion are higher due to greater energy intensity and electricity requirements. Despite this, sodium-ion provides a cost-effective alternative with the potential to de-risk the value chain without compromising performance. Sodium-ion batteries are also not affected by performance issues at cold temperatures, operating between -20 and 60°C. CATL, a leading battery manufacturer, expects to achieve a total cell cost of US$30-45/kWh for sodium-ion batteries using Prussian Blue cathodes. However, the true cost competitiveness of sodium-ion compared to LFP will be realized once economies of scale are achieved and supply chains are solidified.

Figure 5. Sodium-ion versus LFP modelled cost and performance comparison



Source Rho Motion Cell Cost

**Na-ion assumed to be paired with liquid electrolyte, hard carbon anode*

Cost parity with sodium is a challenge for next generation solid-state batteries. There is a possible pathway to cost reduction for all solid-state forms, particularly sulphides and polymers, which offer greater cost reduction and energy density compared to solid-state oxides. However, achieving cost parity with sodium-ion remains a challenge. The introduction of silicon anodes and lithium-metal using chemical vapour deposition methods can lead to cost improvements, particularly for NMC811 cathodes. However, for LFP cathodes, there is no clear route to cheaper cell costs compared to current state-of-the-art technology. Optimized sulphides and polymers, paired with anodes, offer double the energy density of sodium-ion, faster charging times, and enhanced safety. Cost reductions may be possible from thinner separators and cheaper electrolyte materials. However, lithium metal anodes require significant optimization to achieve cost parity with silicon-dominant anodes, particularly because the cost of lithium metal thickness is influenced by production processes, and thinner lithium requires additional treatment.

Opportunities and challenges for further UK research, policy and legislation

For the UK to be successful in the energy transition to 2050, further research and development are required to improve cost competitiveness and performance. Potential research activities are outlined below in the following topic areas:

- **Silicon anodes and lithium anodes**: Silicon anodes are anticipated to be the next major innovation, significantly increasing cell level energy densities and fast charging capabilities. Research opportunities exist to reduce anode precursor costs, explore chemical vapour deposition (CVD) methods for improved anode performance, and pre-lithiation of pure silicon anodes. Lithium metal faces technical challenges and cost trade-offs. UK research efforts should focus on anodes that reduce material volume, with a particular emphasis on lithium metal using CVD methods and alternative current collector materials.

- **Solid-state electrolytes**: Research could focus on silicon anodes paired with polymers or sulphides, and explore lithium metal/oxides for long-term strategies. Sulfide and polymer electrolytes show promise for cost reduction, but oxide-based electrolytes face cost challenges due to catholyte gels. Solid-state technologies also require optimized silicon or lithium-metal anodes while thinner separators can yield significant cost savings at the cell level. Overall, solid-state electrolytes offer improved electrochemical stability, longer cycle life, and battery safety.

- **Sodium-ion batteries**: Although in the early stages of commercialization, sodium-ion batteries offer cost competitiveness, performance parity, and abundant feedstock materials. Potential research areas include improving battery performance and durability through the use of new materials, and by optimizing electrolyte composition. Additionally, addressing safety, reducing environmental impacts, and exploring medium-to-long-term storage applications are other potential areas of research in sodium-ion batteries.

- **Flow batteries**: Research is currently primarily focused on vanadium-flow, zinc-flow and lead/lead oxide chemistries, with limited attention to other flow battery types. Flow batteries offer advantages such as scalability, longer cycle life, and extended storage duration. Vanadium is the preferred chemistry, but cost and toxicity remain areas of concerns. Exploring alternative electrolytes with different transition metals could reduce costs. Architectural design is important as flow batteries are not sealed units. Modular approaches allow interchangeability based on demand. Potential areas for research include electrolyte size, pump rates, electrolyte storage, and electrode interface size.

- **Metal-air batteries**: These types have gained interest for large-scale, long-duration energy storage, but efficiency, cost, and durability issues hinder widespread deployment. Compared to other battery technologies, there has been limited research and development on metal-air batteries, especially in the exploration of materials for the Oxygen Reduction Reaction (ORR) to improve their efficiency.

- **Battery management systems**: BMS research, which in BESS lags behind EVs, could examine battery degradation prediction, improved thermal management, real-time control systems for charging/discharging, managing renewable energy source variability, and predictive modelling. Developing thermal management systems for more cost-effective battery packs through passive heating and eliminating liquid cooling is another avenue for exploration.

In conclusion, lithium-based batteries and LFP chemistries, are expected to dominate the energy storage landscape to 2050. Sodium-ion and redox flow batteries show promise for various grid applications and are expected to gain traction going forward. Further research is needed to improve cost competitiveness and performance in areas like solid-state electrolytes, sodium-ion batteries and flow batteries to succeed in the energy transition.

1. Introduction

Aims and objectives

This study aims to evaluate the scope, nature, and technical features of grid-scale stationary energy storage that would contribute to achieving the goal of Net Zero. Additionally, the study aims to determine the most suitable existing and future energy storage technologies that could meet the UK's requirements and outlines some priorities for scientific research in the UK.

The **principal objective** of this study is to concentrate on the **electrochemical** storage of energy, which primarily involves battery technologies. This includes lithium, sodium, liquid metal, redox flow and hybrid flow batteries, along with any other potential electrochemical compositions that may enter the market within the next decade.

The project is structured around five focus areas:

- **Focus Area 1**: Map the full landscape of grid-scale stationary storage applications (or services) required to deliver Net Zero in the UK.
- **Focus Area 2**: Assess the scope, type and technical characteristics of each energy storage application (service) required.
- **Focus Area 3**: Evaluate and identify the most suitable technologies for each application (service).
- **Focus Area 4**: Assess the performance characteristics specifically required for any battery technologies identified, covering the cost, volume, energy, safety, other characteristics etc.
- **Focus Area 5**: Identify the implications for the Faraday Institution and the UK's scientific research programme.

Analysis methodology

This study was compiled using a combination of online literature, Rho Motion's databases and modelling, and insight from industry experts. An assessment of the UK electricity grid was conducted to identify the flexibility required to manage the UK transition to Net Zero. Key grid flexibility metrics associated with renewable integration were then identified to assess the characteristics of each application required to manage flexibility. These flexibility applications were then categorised depending on the position within the UK power system value chain.

The metrics were then used to assess the suitability of existing ESS technologies for each grid flexibility application. This included, for example, any dependencies on storage duration, geographical constraints, and power demand. A more detailed assessment was then conducted for BESS technologies, with a particular focus on lithium-ion, sodium-ion, metal-air and vanadium flow batteries. By comparing BESS technologies with the current UK energy policy and legislation, potential gaps were identified that require attention to support the scaled implementation of flexible capacity.

Rho Motion's bottom-up *Cell Cost Model* was used to assess the CAPEX and OPEX costs of lithium-ion batteries and to identify the main cost drivers. An assessment of

BESS technology performance and energy was conducted to evaluate the suitability of each technology and associated grid flexibility applications.

During each focus area of the study, Rho Motion assessed and identified potential areas for further research in the UK.

Table 2. Summary of analysis

<table>
<tr><th>Focus Area 1
UK Electricity Grid & Flexibility Needs</th><th>Focus Area 2
ESS Assessment</th><th>Focus Area 3
ESS Suitability</th><th>Focus Area 4
Battery Chemistry Assessment</th></tr>
<tr><td>UK electricity grid/market
<i>Analysis based on</i>
• UK Net Zero transition
• Renewable forecast
• UK energy market

Grid flexibility needs
<i>Analysis based on</i>
• UK electricity flexibility applications & services</td><td>ESS rollout in the UK
<i>Analysis based on</i>
• Current and future ESS landscape
• ESS demand outlook

ESS technology trends
<i>Analysis based on</i>
• ESS technology landscape
• ESS by application, duration and location</td><td>ESS suitability vs grid application
<i>Analysis based on</i>
• ESS performance characteristics
• ESS by application, duration and location</td><td>Battery ESS technologies
<i>Analysis based on</i>
• BESS UK forecast
• Global and UK BESS trends
• Battery technology by application

Battery ESS characteristics
<i>Analysis based on</i>
• Battery performance, energy and cost characteristics
• Drivers and enablers for scaled UK rollout</td></tr>
<tr><td colspan="4">Focus Area 5
Potential areas for further UK research</td></tr>
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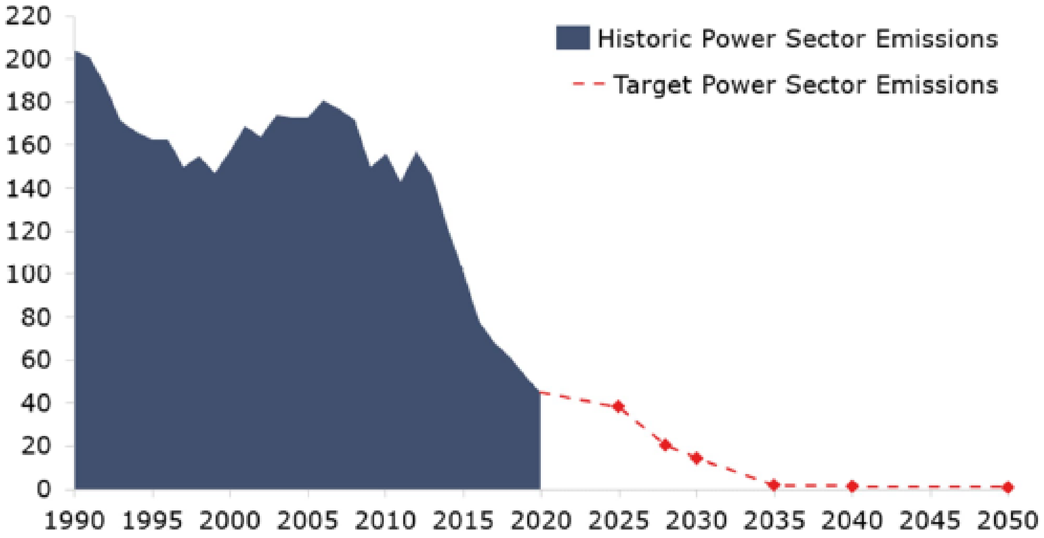
2. UK grid flexibility requirements to deliver Net Zero

This section assesses the need for flexible grid solutions as the UK transitions towards Net Zero. The analysis includes a summary of the electrical grid demand and supply, geographical restrictions, and overall grid stability. Finally, an overview of the different system needs, and associated flexibility solutions is presented.

The Net Zero ambition

The UK has a legal obligation to achieve Net Zero emissions by 2050, which implies a significant overhaul of the energy system. This involves actions such as the government's promise to meet 'Carbon Budgets' and attain decarbonisation of the power industry by 2035, as illustrated by the pathway set by the Climate Change Committee (CCC) in Figure 6.

Figure 6. CCC's Balanced Pathway (MtCO2e) target and historical gross power sector emissions



Source *Climate Change Committee (2020). The Sixth Carbon Budget.*

In response to recent geopolitical challenges associated with energy security, the UK Government has increased its commitment to the energy transition. The British Energy Security Strategy[1] aims to decrease international reliance on fossil fuels while increasing the use of clean energy sources. This is viewed as essential to reduce the UK's dependence on costly and unstable fossil fuels, whose prices are determined by international markets, and to ensure long-term energy security.

Electrical grid outlook by 2050

While it is anticipated that future UK energy demand will decrease, there is an expectation of a rise in electrical demand, primarily driven by various industries moving away from fossil-based fuels. The CCC balanced Pathway scenario[2] forecasts annual electricity demand to be 50% higher than 2019 figures by 2035, as shown in Figure 7.

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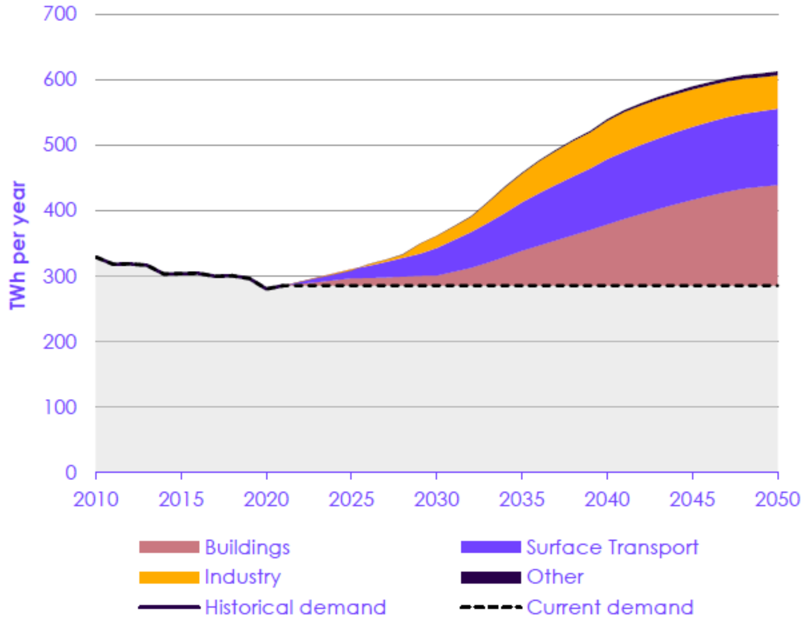
[1] HM Government (April 2022). British Energy Security Strategy.

Figure 7. UK electricity demand is set to increase to 2050

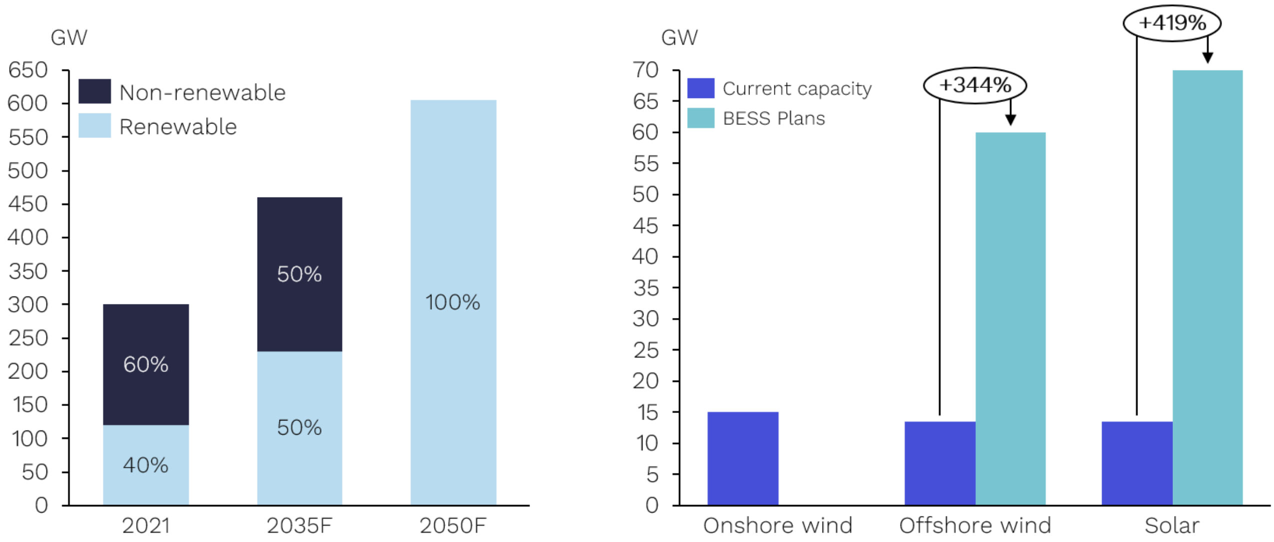


Source [*BEIS (2022) Energy Trends; CCC (2020) The Sixth Carbon Budget.*]

While many industries shift towards more electricity use, there could also be a shift to hotter summers and wetter winters.[2] As a result, there will be a greater need for a reliable, stable, and secure electricity supply alongside increased demand.

The UK government has set ambitious renewable electricity supply percentage targets of 50% by 2035 and 100% by 2050. In 2021, the share of renewable electricity generation was 39.7%, with wind power attributing to the highest share of 24.6%.[3]

Figure 8. Renewable generation (in GW) and renewable capacities (in GW)



Source *HM Government (2022). British Energy Security Strategy (BESS)*.

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[2] *Climate Change Committee (2020). The Sixth Carbon Budget.*

[3] Met Office (2019). UK Climate Projections: Headline Findings.

[3] BEIS. UK Energy in Brief 2022

It is expected that the majority of renewable generation will consist of intermittent renewables, particularly solar and wind. Recent technological innovations have improved the efficiency of solar and wind energy generation. Outside of the capital investment required, these energy generation methods are now the most affordable form of energy generation per MWh produced in the UK, as depicted in Table 3.

Table 3. 2020 levelised cost estimates for different forms of UK electricity generation

Electricity Generation Method	The proportion of UK Electricity Production	Cost (GBP/MWh)
Combined Cycle Gas Turbine	39.8%	85
Offshore Wind	12.6%	57
Onshore Wind	10.8%	46
Large Scale Solar	1.5%	44

Source *BEIS Electricity Generation Costs 2020*.

Moreover, two-thirds (163GW) of newly installed renewable capacity in G20 countries in 2020 had lower costs than the cheapest fossil-fuel alternative[4]. The UK government envisages increasing offshore wind four-fold by 2030 and solar capacity five-fold by 2035, as shown in Figure 9.

Renewables, particularly intermittent wind and solar power are projected to exceed 250GW by 2050, and electrification of heating, transportation, and some industrial processes could result in final electricity consumption being double current levels by 2050. The Energy Security Strategy sets out ambitious targets for the UK Government, including 50GW of offshore wind power by 2030 and 70GW of solar energy by 2035. Successfully integrating these technologies into the UK energy system is crucial to ensuring that sufficient low carbon power is available to meet the country's energy needs. However, there are several key challenges to overcome, including balancing supply and demand over different time horizons, addressing locational constraints, and adapting to a low-inertia system.

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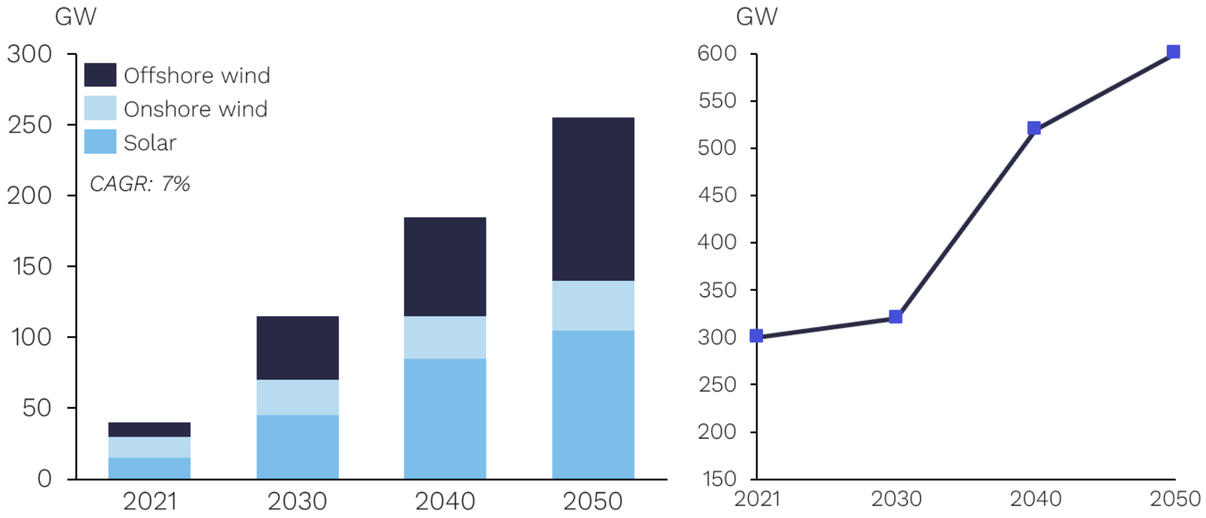
[4] IRENA, Renewable Power Generation Costs (2021).

Figure 9. Renewable capacity outlook by 2050 and CCC electrical demand to 2050



Source *Climate Change Committee (2020). The Sixth Carbon Budget.*

Grid flexibility to complement transition to Net Zero

Operationally, the main goal of the UK grid is to ensure there is enough supply of electricity to meet demand, across a complex array of end-use types including transportation, buildings, and industry. Imbalances between electrical supply and demand can result in costly equipment damage, power interruptions and failures. There is also an important need for additional balancing management needs, such as ancillary services.

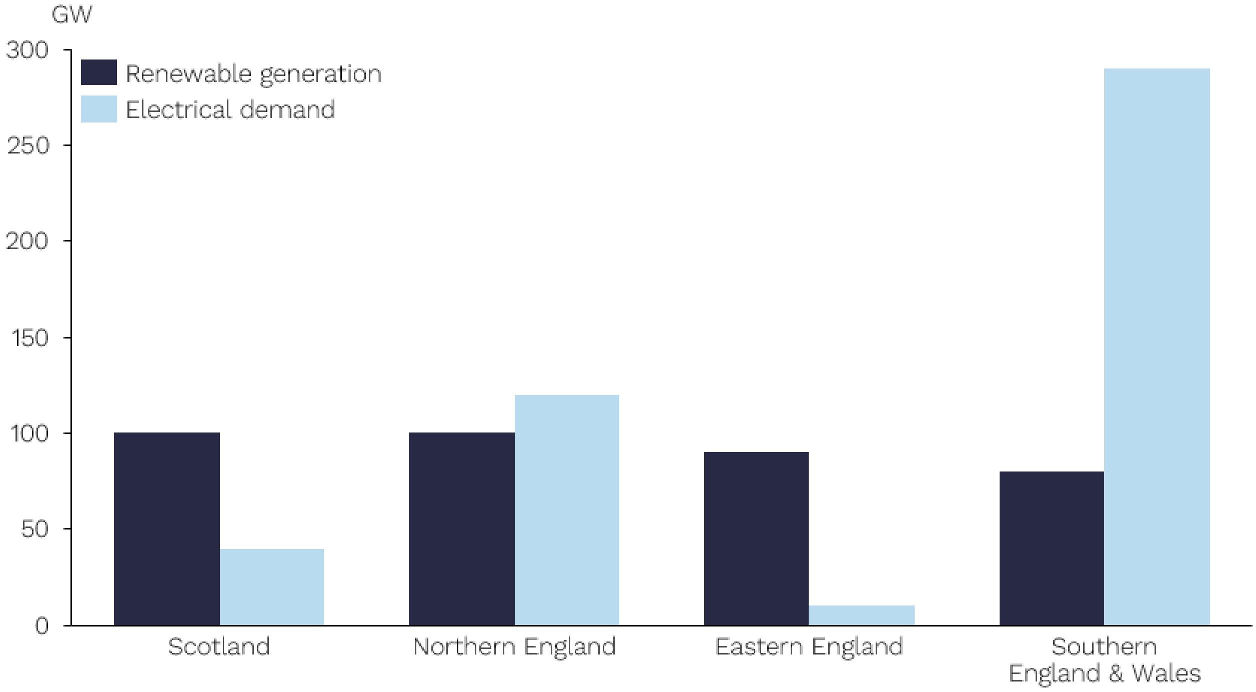
As the UK grid prepares for bulk deployment of intermittent renewable generation over the next two decades, this will further emphasise the need for a reliable, secure and resilient grid. To manage this fundamental shift in electricity supply, it will require tackling the following four key grid challenges:

1. **Decentralised renewable locations** – optimising renewable (wind and solar) sites relative to local demand.
2. **Synchronising renewable integration** – minimising the effects of non-synchronous renewable generation.
3. **Energy management systems** – improving energy efficiency via demand-side energy management.
4. **Intermittent renewable generation** – minimising effects of intermittent renewable supply versus daily demand patterns.

Decentralised renewable locations

Currently, wind and solar site locations are selected based on renewable sources, network connection availability and land agreements. As a result, the geographical relationship between electrical supply and demand is not directly related, as illustrated in Figure 10. By 2035, it is forecast that Scotland will produce more electricity than it consumes. Conversely, Southern England and Wales's electricity demand will be approximately three times greater than what they can renewably generate.

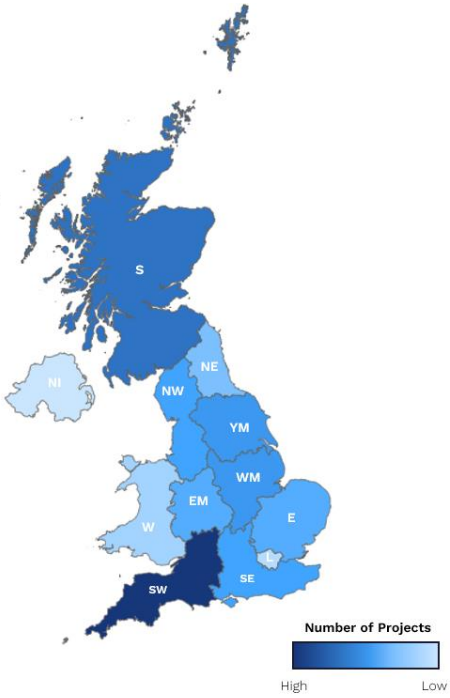
Figure 10. UK regional renewable generation and demand by 2035



Source *[Climate Change Committee (2020). The Sixth Carbon Budget.]*

The distribution and concentration of BESS projects in relation to renewable sources can vary across different regions in the UK due to several factors: Resource availability, grid infrastructure capabilities, local demand patterns, and regulatory considerations. It is a complex interplay between these factors that determines the optimal locations for deploying BESS projects. South-West England has the highest installed BESS capacity of 324MWe (Figure 11), followed by Scotland with 204MWe, while the rest of the UK exhibits a relatively even distribution of BESS installed capacity, with the exception of London, Northern Ireland and Wales.

Figure 11. Geographic distribution of BESS projects within the UK, in April 2023



Region (key)	Number of Projects*	Installed Capacity (MWe)
East Midlands (EM)	9	116
Eastern (E)	7	110
London (L)	2	0.2
North East (NE)	5	89
North West (NW)	8	205
Northern Ireland (NI)	1	10
Scotland (S)	12	204
South East (SE)	8	72
South West (SW)	17	324
Wales (W)	3	22
West Midlands WM)	7	87
Yorkshire and Humber (YM)	9	256

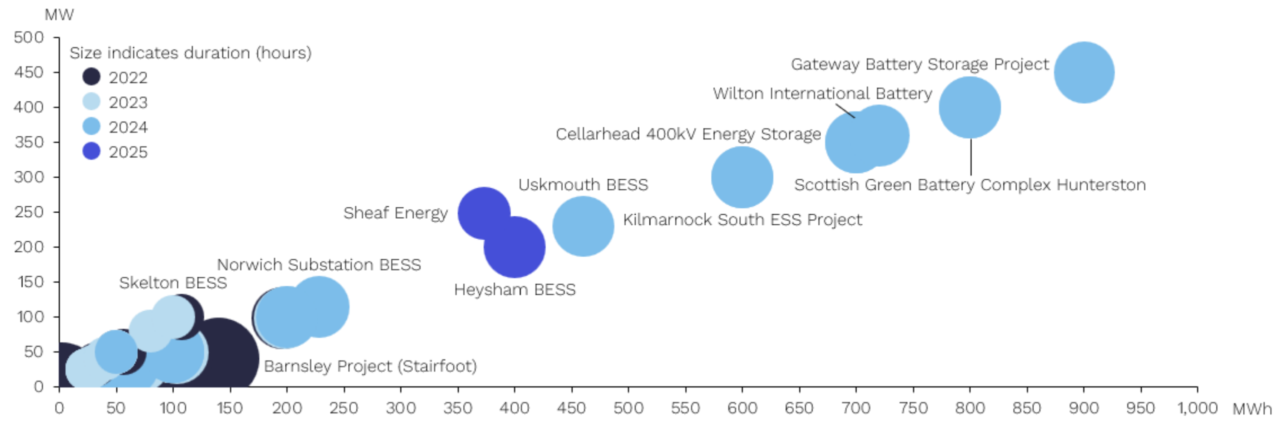
** Operational*

Source *[Department for Energy Security and Net Zero]*.

The outlook for BESS projects in the UK is promising, with a significant pipeline of projects anticipated. The BESS pipeline not only entails a rise in the number of projects but also encompasses larger-scale projects of extended storage durations.

Looking specifically at the period from 2023 to 2025, there is a substantial pipeline of lithium-ion BESS capacity totalling over 10GWh that has already received planning approval, shown in Figure 12. These projects are at various stages of development, and their implementation is expected to contribute significantly to the overall expansion of BESS capacity in the UK.

Figure 12. UK BESS project pipeline between 2022-2025



Source Rho Motion

Synchronising renewable integration

Synchronising energy assets is key to ensuring a smooth and uninterrupted transmission of the supply of electricity to end users. As renewable intermittent supply ramps up, it will adversely decrease grid inertia. Grid inertia refers to the energy system's ability to resist frequency changes caused by fluctuations in electricity supply and demand. It is primarily derived from the rotating mass and kinetic energy of conventional generators, such as coal or gas plants, which help stabilise the grid. As renewable energy sources, such as wind or solar, increase their share in the UK energy mix, the reliance on conventional generators decreases. This can lead to reduced voltage stability as a result.[5] Moreover, as weather is an unpredictable variable it will result in larger errors in electricity supply forecasting.

Energy management systems

One approach to managing electricity flexibility is through demand management. This involves reducing the need for electrical generation or storage during peak demand periods and minimising the required network capacity without compromising the end user. Smart demand shifting, such as controlled timing of EV charging and smart management of heat pumps and appliances, can help to smooth peaks in demand and absorb excess supply. As the UK further electrifies the transport and heating sectors, the potential need for demand management will increase.

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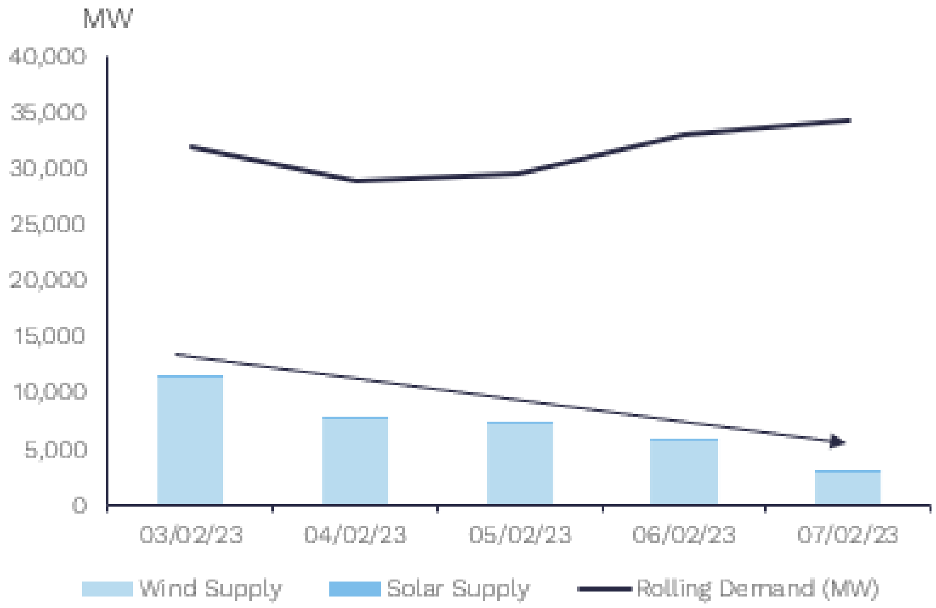
[5] NGESO Operability Strategy Report (2022).

Intermittent renewable generation

As renewable generation is set to form the backbone of electricity generation over the next two decades, the grid will face key challenges in balancing supply and demand given the intermittent inconsistencies in relation to a specific weekly demand period, as shown in Figure 13. For example, over five days across 3-7 February 2023, electricity demand remained relatively consistent. However, renewable generation (wind and solar) declined by over 5000MW. Scaling renewable generation would cause an insufficient supply of electricity while, conversely, the same would apply if there was an excess renewable generation.

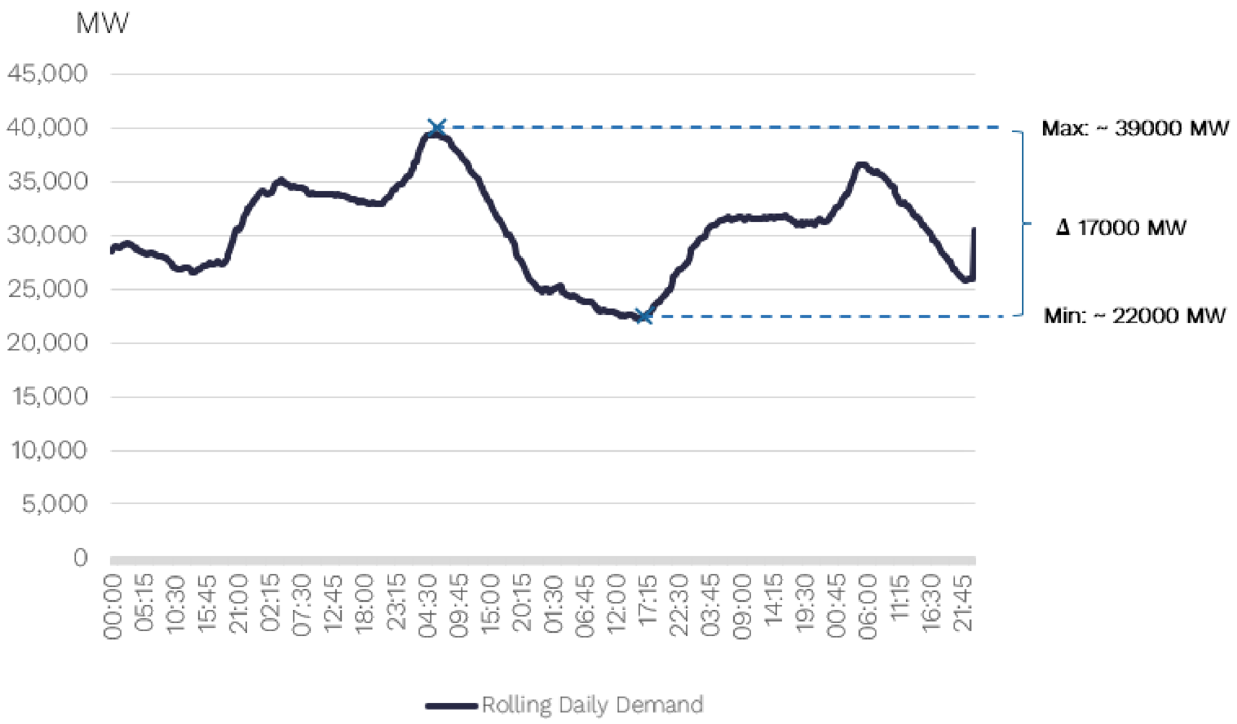
Figure 13. Fluctuation in renewable generation and electricity demand over a five-day period



Source *ESO, Elexon BMRS*. (Electricity Storage Operator)

Another important issue to consider is the fluctuations in daily electricity demand. For example, between 7 February 2023 and 14 February 2023, there was a difference of 17000MW between the maximum and minimum electricity demand within the seven-day period, see Figure 14, which also illustrates a daily demand and supply cycling pattern.

Figure 14. The electrical demand profile exhibits daily cyclical behaviour over a seven-day period



Source *Elexon BMRS*.

Flexibility is essential for shifting the consumption or generation of energy in terms of time or location. As renewables become more prevalent in the generation mix, there is greater variability in generation patterns due to weather conditions, which results in more variation in residual demand position. Adequate flexibility provision is critical to delivering a cost-effective and secure power system as the country decarbonises towards 2035. Electricity flexibility is particularly needed to ensure the sufficient management of supply and demand over varying time frames, ranging from hourly, daily, monthly, and seasonal cycling. Moreover, it highlights the important requirements of steep electrical upward and downward ramping capabilities, i.e. the ability to quickly increase or decrease electricity production in response to changes in demand.

Implications for Energy Stationary Storage

The substantial increase in renewable energy generation poses significant challenges for maintaining grid stability. Geographical imbalances between supply and demand, the need to synchronise energy assets, increased use of demand management, and the unpredictability of renewable generation underscore the need for robust and responsive grid management strategies. In this context, ESS can play a crucial role as a pivotal instrument to provide the necessary flexibility.

ESS can act as a buffer, capable of storing excess energy during periods of high renewable supply and dispensing electricity during periods of high demand or when renewable output is scarce. By capturing and storing renewable energy when supply exceeds demand, ESS helps to balance supply and demand dynamics, reducing the reliance on immediate generation capacity.

Deploying ESS strategically across the grid allows for the optimisation of renewable energy utilisation, grid balancing, and improved overall system reliability. By effectively integrating renewable generation with storage capabilities, the grid can enhance its resilience and adaptability to changing conditions.

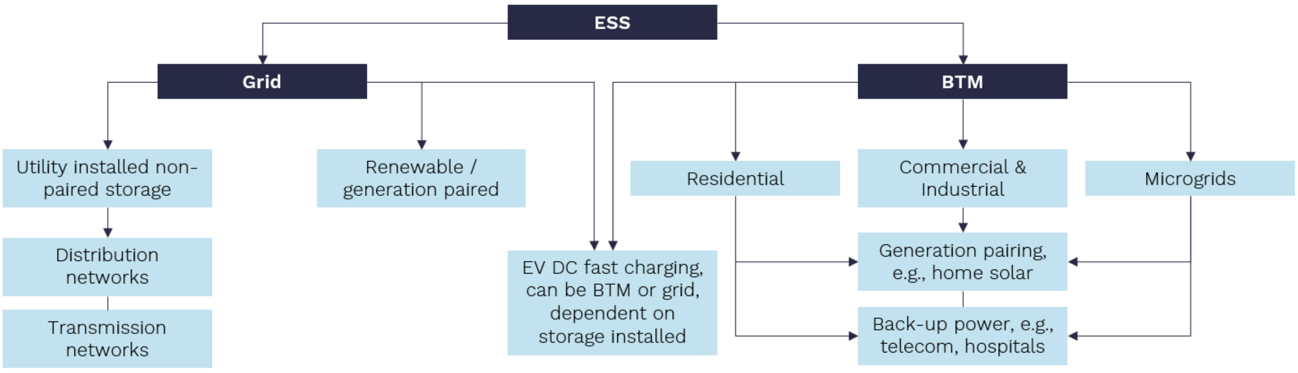
3. The role of energy stationary storage solutions in enhancing grid flexibility

This section provides an analysis of the role of energy storage solutions specific to grid applications, namely different technologies used to manage power system flexibility and their suitability. It examines the current landscape of grid flexibility technologies, with a focus on the growing importance of BESS and challenges related to long-duration energy storage.

Energy stationary storage (ESS) applications are broadly split into two main categories, as shown in Figure 15:

- **Front-of-the-meter (Grid),** storage connected to distribution or transmission networks, or in connection with electricity generation, also known as ''front-of-the-meter''.
- **Behind-the-meter (BTM)**, decentralised form of storage interconnected behind the utility meter of commercial, industrial, or residential customers, primarily aiming at electricity bill savings, including microgrids with no access to the grid.

Figure 15. ESS applications, split into Grid and BTM



Source Rho Motion

Grid flexibility application requirements

As the proportion of renewable electricity generation with variable or limited output grows, the need for flexibility in the power system becomes more crucial. Energy storage is a key solution that offers flexibility through the provision of a diverse range of applications.

There are 10 key applications for managing power system flexibility, which can be classified into three broad flexibility roles:

1. System Stability & Reliability
2. Reducing Geographical Limitations
3. Managing Demand & Supply

These roles cover major parts of the power system including the grid, network and end-use as detailed in Figure 16, while Table 4 provides a more detailed description of electricity storage application types and how they are positioned relative to the power system stage. Applications are mostly focused on 'Generation' to manage and optimise electricity production and 'Network' to maintain system stability and facilitate efficient power transfer throughout the electricity grid.

Figure 16. Grid flexibility roles as a function of the power system stage

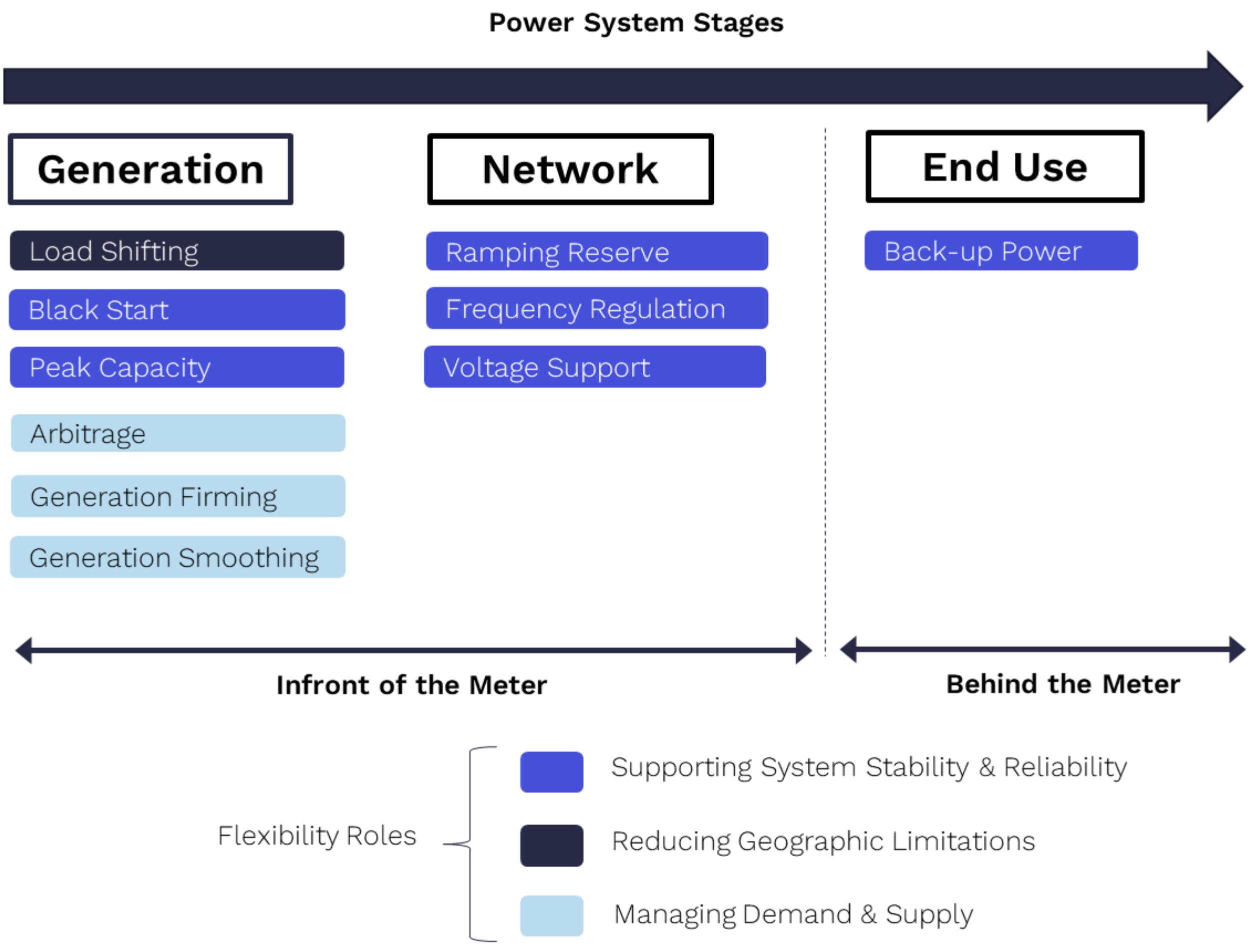


Table 4. Summary of the most common grid flexibility applications

Energy Flexibility Application	Power System Stage	Description
Load shifting	Generation	Adjusting regionally the timing of electricity use from peak periods to off-peak periods to help balance the grid and avoid overloading it during high demand periods.
Black start	Generation	The ability to restart a power station or part of the grid after a complete power outage.
Peak capacity	Generation	The ability to meet the highest level of demand for electricity during peak periods.
Arbitrage	Generation	Buying electricity when it is cheaper and selling it when it is more expensive to make a profit.
Generation firming	Generation	Using energy storage to store excess renewable power output to be used later.
Generation smoothing	Generation	Using energy storage to smooth out fluctuations in power output from renewable energy sources.
Ramping reserve (frequency response)	Network	Adjusting and stabilising frequency due to unexpected changes in demand or supply.
Frequency regulation (ancillary services)	Network	The process of maintaining the frequency of the power system within a narrow range. This is done by adjusting the electricity supply to match the demand in real time.
Voltage support (ancillary services)	Network	The process of maintaining the voltage levels in the power grid within acceptable limits to ensure the efficient and safe operation of electrical devices.
Backup power	End Use	Provide electricity during unexpected periods of low or no electricity supply.

Source Rho Motion

The specific requirements for common grid flexibility applications may vary depending on the market. For instance, some resilient power systems may only have a black start event once every decade, while less robust systems may encounter multiple black start events in a year.

ESS grid applications require careful consideration of several key performance indicators (KPIs) to ensure grid flexibility and stability, as depicted in Table 5. These KPIs play a crucial role in determining the effectiveness and suitability of ESS for specific applications.

In the context of the UK's energy landscape, certain KPIs hold significant importance. One such KPI is response time, which refers to the speed at which the storage system can respond to the demand for its application. A quick response time is essential for effectively addressing fluctuations in the grid and maintaining stability. Another critical KPI is the discharge duration of the storage system, indicating the amount of time it can discharge at its power capacity before depleting its energy capacity. The discharge duration depends on the size and intended application of the storage system.

Table 5. Key performance indicators for ESS applications

KPI	Unit	Priority	Notes
Response time	ms – hour	High	The amount of time the storage system takes to respond to a demand for its application
Discharge duration	ms – hour	High	The amount of time storage can discharge at its power capacity before depleting its energy capacity, thus becomes a function of size and application
Roundtrip efficiency	%	Moderate-High	Indicates the lossless transmission of energy i.e., how much energy is lost per cycle
Power capability	W	Moderate-High	Highly dependent on the application, e.g., Uninterruptible Power Sources (UPS) might require high power versus ESS for peak shaving
Cycle life and lifetime	Cycle n, years	High	Applications generally require long life i.e., greater than 3,000 cycles over 10-15 years of operation
Gravimetric energy	Wh/kg	Low	Low relevance besides on a cost per kWh basis
Volumetric energy	Wh/L	Low-moderate	High energy reduces the cost per unit basis, and volumetric is more relevant than gravimetric (e.g., facility footprint)
Safety	Standard testing	High	Safety cannot be compromised; however, the importance of safety is amplified by scale (e.g., >1MWh)
System cost	US$/kWh	High	Cost per kWh is the standard metric to measure cost on a per unit basis, however, cost per cycle can be important considering that ESS can have long life i.e., incurs CAPEX and OPEX, and generates revenue
End-of-life cost, sustainability	US$/(kWh CO_2e), recovered content	Moderate	The cost of system disposal must be considered when designing a stationary storage asset. With increasing legislative pressure, minimum threshold requirements are expected to be enshrined into law

Source Rho Motion

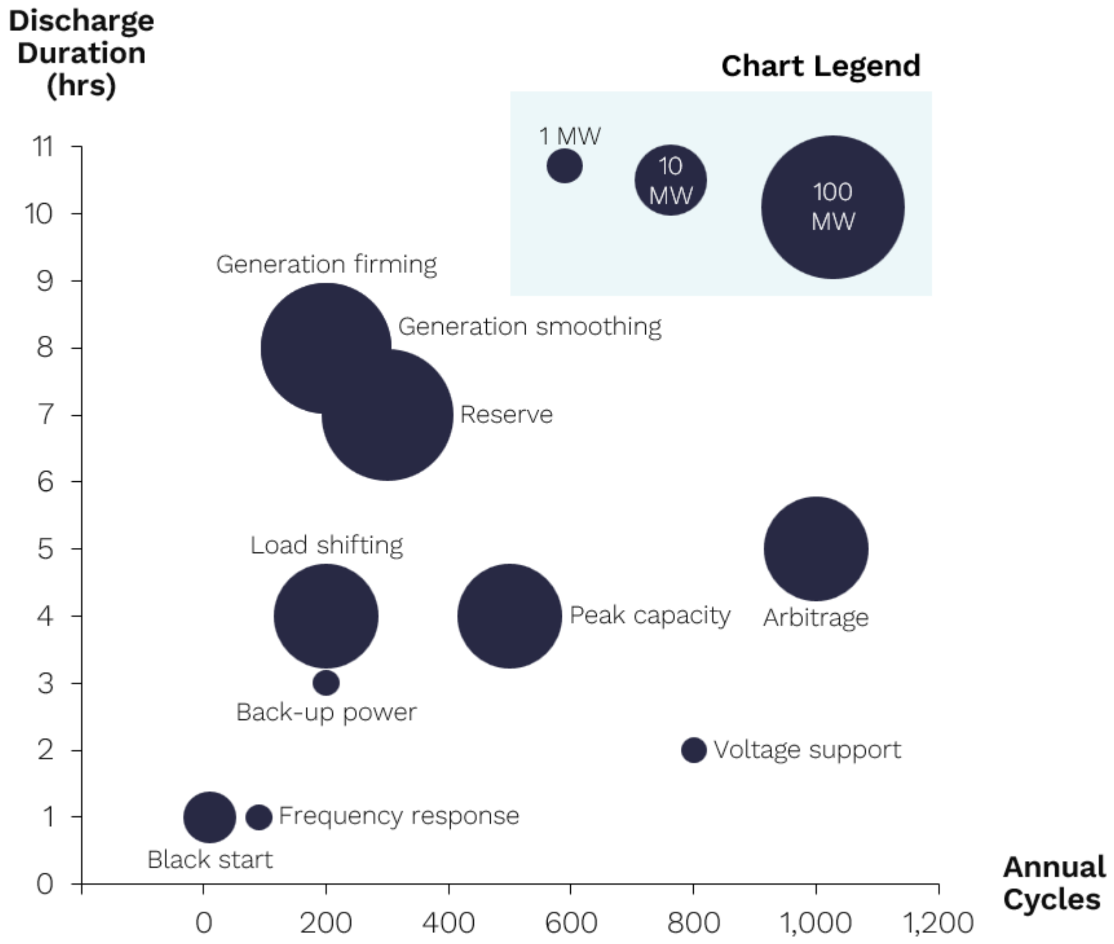
Safety is also a critical performance metric that has gained increasing importance, particularly for larger-scale ESS deployments exceeding 1MWh. Ensuring the safe design, construction, and operation of ESS equipment is paramount to protecting personnel and the surrounding environment.

Furthermore, system cost emerges as a high-priority KPI, commonly measured in terms of cost per kilowatt-hour (US$/kWh). It serves as a standard metric for assessing the economic viability of ESS technologies on a per-unit basis. However, it is equally important to consider the cost per cycle, considering the long life and revenue generation potential of ESS systems. This consideration encompasses both capital expenditure (CAPEX) and operational expenditure (OPEX).

Flexible applications and performance metrics on their own do not encompass the entire scope of flexibility requirements. They typically also diverge by two fundamental operational requirements: i) the number of cycles, and ii) discharge duration. Both of these factors are cross-plotted to determine which technology could be most suitable for each flexibility application, as shown in Figure 17.

The annual cycle and discharge duration requirements for these applications are selected from commonly observed ranges in different markets to encompass the entire spectrum of cycle and discharge duration requirements.

Figure 17. Summary of grid flexibility requirements, with circles providing a function of MW size



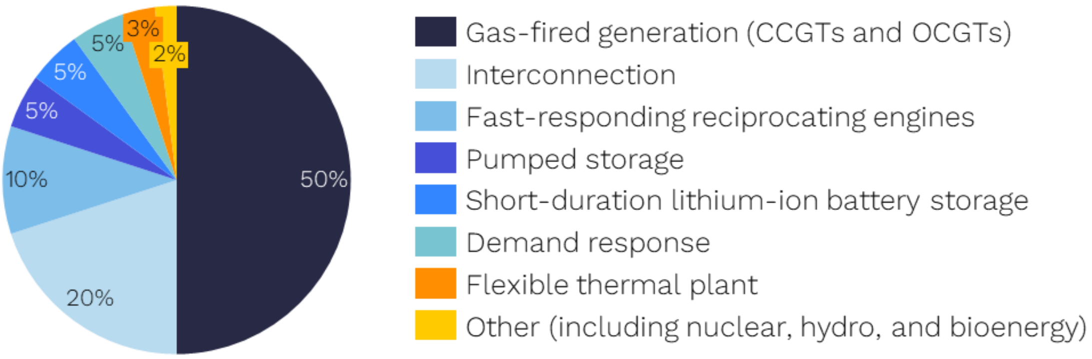
Source Rho Motion

Technology suitability for each grid flexibility application

Currently, the provision of electricity system flexibility is heavily reliant on the supply side, with gas-fired generation accounting for a 50% market share in 2021, as illustrated in Figure 18. Combined Cycle Gas Turbines (CCGTs) and Open Cycle Gas Turbines (OCGTs) play a key role in providing system flexibility while reciprocating engines that can respond quickly to changes in demand have also become more prevalent in recent years.

Additional flexibility is provided by a limited number of pumped storage plants and almost 2GW of short-term lithium-ion battery storage. Increased levels of interconnection and demand response have also contributed to the existing flexibility. However, the reliance on thermal power generation without emission mitigation measures, known as unabated thermal capacity, cannot continue as emission constraints will likely be imposed by the UK Government. Alternative flexible solutions will therefore be required to manage the evolving renewable electricity supply and demand pattern.

Figure 18. UK grid flexibility technology landscape in 2021



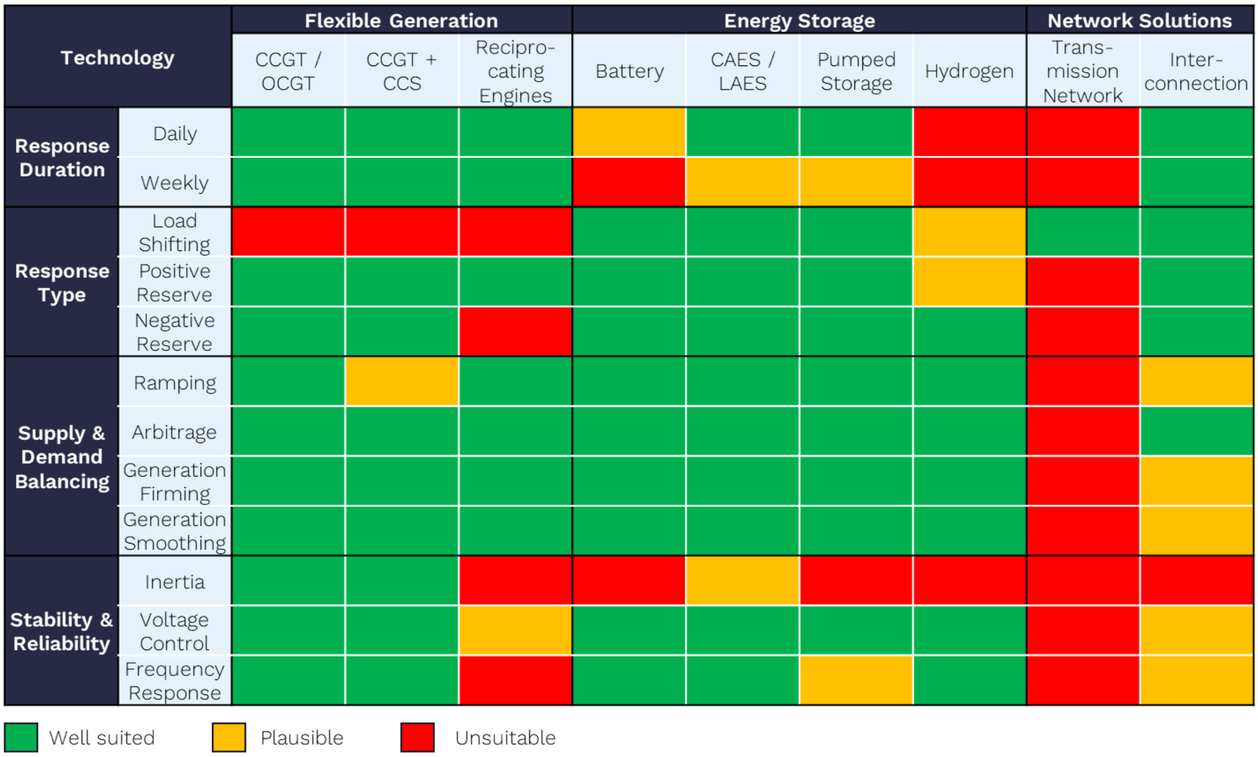
Source *ESO Future Energy Scenarios 2022*.

Technologies currently deployed in grid applications

The technologies used for energy storage systems include BESS, compressed air storage (CAES), liquid air energy storage (LAES), pumped hydro storage (PHS) and potentially hydrogen

To achieve Net Zero, the electricity system will require both rapid and prolonged flexibility solutions. Table 6 shows the different technologies available, and which are best suited to deliver the different grid flexibility requirements such as flexible generation, energy stationary storage and network solutions. The various flexibility applications provide different types of flexibility over different time periods and in varying combinations. Combined, they provide the flexibility needed across the landscape, supporting the UK in achieving Net Zero. For instance, while many flexible generators can provide response services of longer duration, they may not be able to provide the load-shifting capability that many energy storage technologies can offer. Conversely, network solutions offer a finite set of flexibility offerings, particularly geared for load shifting and negative and positive reserve management.

Table 6. Summary of the grid flexibility technologies vs flexibility application



Technology		Flexible Generation			Energy Storage				Network Solutions	
		CCGT / OCGT	CCGT + CCS	Reciprocating Engines	Battery	CAES / LAES	Pumped Storage	Hydrogen	Transmission Network	Interconnection
Response Duration	Daily	🟩	🟩	🟩	🟨	🟩	🟩	🟥	🟥	🟩
	Weekly	🟩	🟩	🟩	🟥	🟨	🟨	🟥	🟥	🟩
Response Type	Load Shifting	🟥	🟥	🟥	🟩	🟩	🟩	🟨	🟩	🟩
	Positive Reserve	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟥	🟩
	Negative Reserve	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟥	🟩
Supply & Demand Balancing	Ramping	🟩	🟨	🟩	🟩	🟩	🟩	🟩	🟥	🟨
	Arbitrage	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟩
	Generation Firming	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟨
	Generation Smoothing	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟨
Stability & Reliability	Inertia	🟩	🟩	🟥	🟥	🟨	🟥	🟥	🟥	🟥
	Voltage Control	🟩	🟩	🟨	🟩	🟩	🟩	🟩	🟥	🟨
	Frequency Response	🟩	🟩	🟥	🟩	🟩	🟨	🟩	🟥	🟨

🟩 Well suited 🟨 Plausible 🟥 Unsuitable

Source Rho Motion

Longer-duration storage technologies are currently forecasted to be met by a mix of green hydrogen and pumped hydro, potentially reaching somewhere in the range of 11-56TWh of seasonal storage, as shown in Figure 19.

PHS offers high energy capacity and long-duration storage capabilities, making it ideal for large-scale energy storage and balancing of the grid over longer time periods. CAES and LAES also offer high energy capacity but typically have shorter storage durations compared to PHS. They can be used for peaking power and providing grid stability during short-duration demand spikes. [6]

Battery technologies, on the other hand, offer lower energy capacity but can deliver power quickly and efficiently, making them suitable for short-duration energy storage and ancillary services. Different types of batteries, such as lithium-ion, sodium-ion, and redox flow, have different storage durations and power capabilities, which make them suitable for different use cases. The fast response of lithium-ion batteries allows for revenue stacking by participating in various markets, such as wholesale, balancing, capacity, and ancillary services, which will enhance the technology's market performance.

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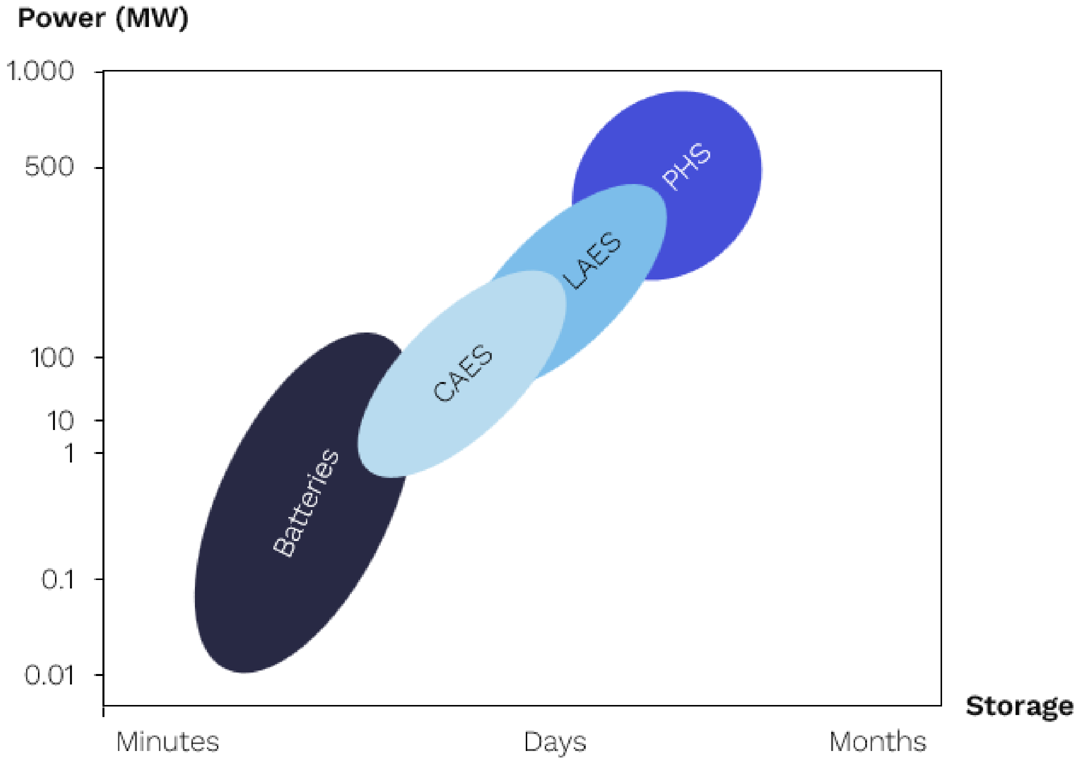
[6] Walker & Lait (2022), Parliamentary Office of Science and Technology. Longer Duration Energy Storage.

Figure 19. ESS landscape as a function of storage duration and power rating



Source Renewable Energy Association

CAES and LAES are key technologies for intermediate duration energy storage solutions. CAES compresses air for storage, while LAES cools and liquefies air. Both are used for demand response and peak shifting, with CAES requiring specific geological conditions and LAES offering broader applicability. These technologies bridge the gap between short-term BESS and longer-duration technology options.

Hydrogen offers the opportunity for seasonal storage in the power sector, although its implementation is currently limited. A detailed discussion of the role of hydrogen in the power sector is given in a recent DNV study for the Faraday Institution.[7]

Flow batteries are expected to show efficiency gains in the future in contrast to lithium-ion batteries, Equally, unlike PHS, flow batteries are not bound by geographical phenomena required for effective installation. Additionally, construction time is also significantly quicker, making them still a viable solution for larger flexibility applications.

Battery technology is more expensive than PHS, CAES and LAES for large-scale projects, but more suitable for smaller-scale applications.[8] One of the main drawbacks of PHS, CAES and LAES technologies is the inherent higher cost per kW, as depicted in

Table 7, which is primarily driven by high capital expenditure associated with civil engineering works and the cost of equipment, such as turbines and generators. As a result, there is the risk that these technologies will not be commercially competitive

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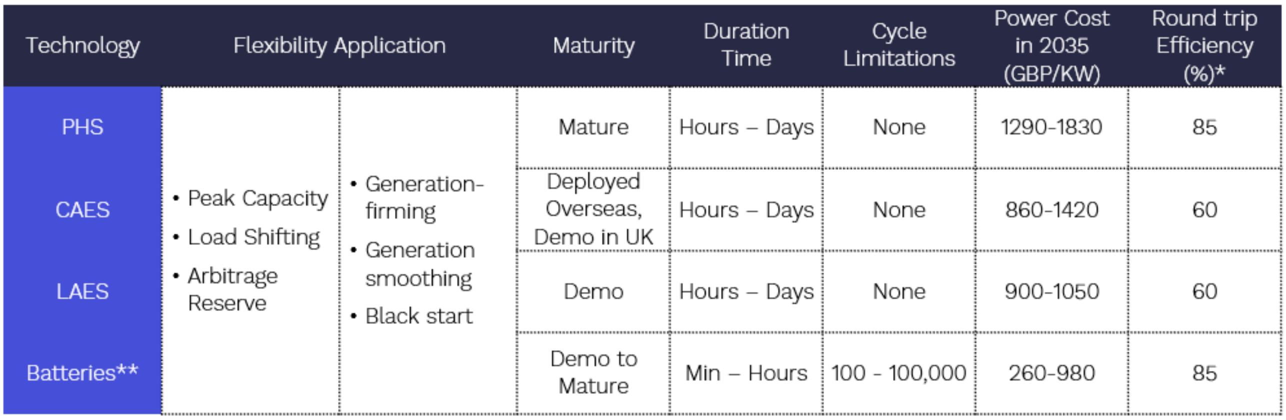
[7] DNV (April 2023). The Role of Hydrogen and Batteries in Delivering Net Zero in the UK by 2050

[8] Kebede et al, 2022. A comprehensive review of stationary energy storage devices.

in providing flexible storage solutions over days to months periods, which will be required for the UK to reach its Net Zero goals.

Table 7. Summary of ESS technology suitability and performance characteristics



Technology	Flexibility Application		Maturity	Duration Time	Cycle Limitations	Power Cost in 2035 (GBP/KW)	Round trip Efficiency (%)*
PHS	• Peak Capacity • Load Shifting • Arbitrage Reserve	• Generation-firming • Generation smoothing • Black start	Mature	Hours – Days	None	1290-1830	85
CAES			Deployed Overseas, Demo in UK	Hours – Days	None	860-1420	60
LAES			Demo	Hours – Days	None	900-1050	60
Batteries**			Demo to Mature	Min – Hours	100 - 100,000	260-980	85

Source Rho Motion

* *Climate Change Committee*.

** Includes lithium-ion, redox flow, sodium-ion and metal-air batteries

Conversely, battery technologies have lower capital costs, but their operating costs may be higher due to the need for periodic replacement of the batteries. The cost and performance characteristics of battery technologies for grid applications will be covered in detail in *Section 6. Impact of battery cost on BESS economic viability.*

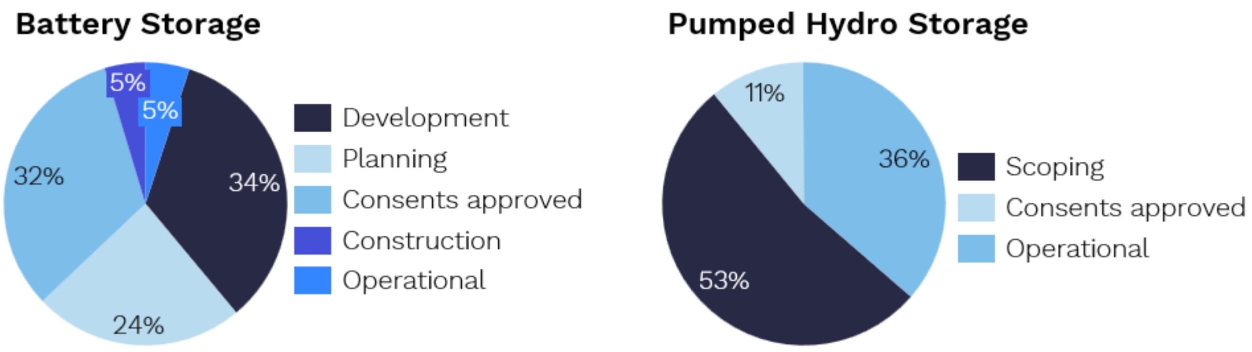
4. UK energy stationary storage market outlook

Current UK grid technology deployment

Most of the UK's grid flexibility, totalling just under 18TWh, currently comes from natural gas.[9] These fossil fuel assets are switched on at short notice to provide 'peaking capacity'. In essence, an injection of supply to the grid to maintain balance in the system. As of 2022, the Grid's non-gas energy storage assets comprised 2.6GWh of pumped hydro and 2.5GWh of BESS[8]. Both are expected to grow significantly to support an increasingly renewable-rich energy generation mix and a decarbonised energy storage system.

Over the past year, the number of battery energy storage projects in the UK's pipeline has increased from 239 to 338 in total[9]. The capacity of battery storage is also set to increase substantially as only 5% of projects in 2022 are in operation, with the remaining 95% of projects in the pipeline, either under construction, development or still in the planning process, as illustrated in Figure 20. In contrast, 36% or 2.7GW of the pipeline of Pumped Hydro Storage (PHS) is currently operational, with the remaining projects either under the scoping phase (3.9GW) or have obtained their consent.

Figure 20. UK battery storage and pumped hydro storage projects in 2022, in GW



Source: ESO Future Energy Scenarios 2022.

Future UK grid technology deployment

The significant growth in the pipeline of battery storage projects is largely due to key changes in legislation and economies of scale i.e., cost reductions. In particular, the UK government amended the law in December 2020 to permit local planning authorities to approve projects with a capacity of over 50MWh in England and over 350MWh in Wales. Before this change, only the central government had the authority to authorise such capacity deployment, making the process more complicated and time-consuming.

The ESO expects battery energy storage to form the largest portion of energy storage by 2050 with 35GWh installed capacity when considering its "System Transformation" scenario forecast, as shown in Figure 21.

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[9] ESO. Future Energy Scenarios 2022.

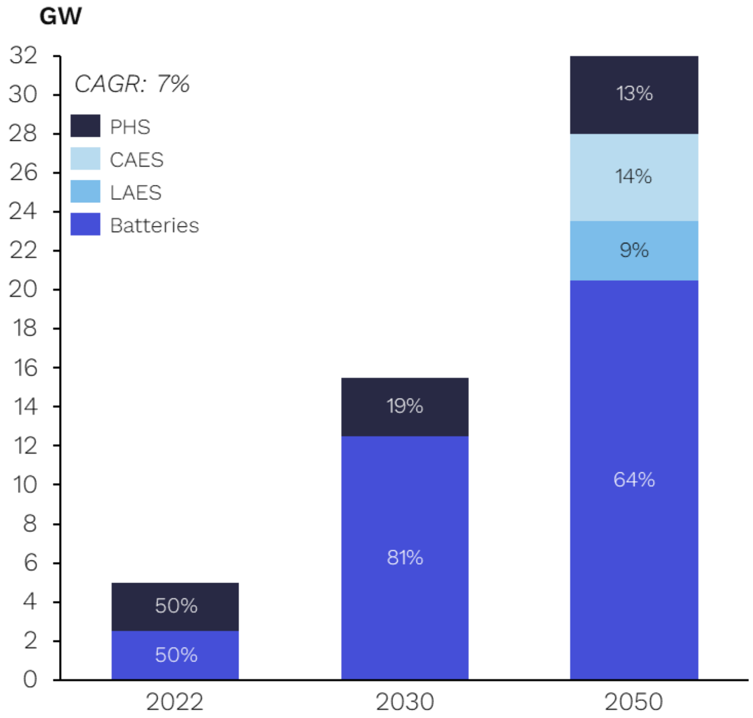
[9] Department of Energy Security & Net Zero Database

Overall, it is anticipated that battery energy storage will form the backbone of flexible energy storage, taking a market share of 81% and 64% of installed capacity by 2030 and 2050 respectively. Within this installed capacity, it is expected that most future stationary energy storage projects in the UK will use lithium-based battery technology, given the dominance of two-hour-duration batteries in the current pipeline. The competitiveness of lithium-based batteries is expected to improve because of lowering costs driven by further economies of scale; a response to the burgeoning EV market and demand for an improvement in energy density.[10]

PHS will continue to contribute to the energy flexibility landscape as new projects come online, but the technology will be inherently constrained by long lead times and geographical restrictions. Moreover, PHS is considered a mature technology and, as a result, is expected to forego significant techno-economic improvements in energy/power capital costs or its round-trip efficiency.[11]

Similarly, CAES will see further adoption, with adiabatic CAES presenting an opportunity for a reduction in capital costs versus diabatic CAES. Adiabatic CAES involves compressing and storing air without heat exchange, while diabatic CAES includes heat exchange with the surroundings during compression and storage processes. The deployment of LAES is more limited in comparison to PHS and CAES due to fewer companies offering this technology. Consequently, the potential for significant economic improvements is limited due to the lack of economies of scale. An important advantage of LAES is that it is not geographically constrained, which can offer wider deployment opportunities depending on the commercialisation rates.

Figure 21. UK ESS current and projected installed capacity



Source *ESO Future Energy Scenarios, System Transformation Scenario 2022*.

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[10] Schmidt, Melchior, Hawkes and Staffell (2019). Projecting the Future Levilised Cost of Electricity Storage Technologies.

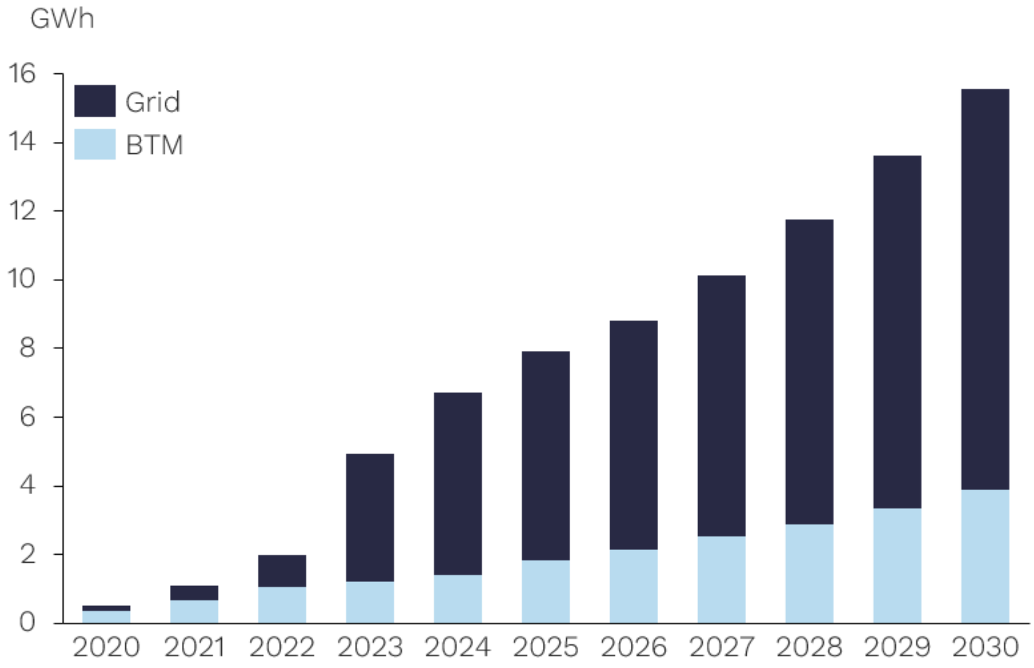
[11] Tsiropoulos, I., Tarvydas, D. ,Zucker, A (2018) Cost Development of Low Carbon Energy Technologies to 2050.

UK Outlook for BESS deployment

The landscape of battery chemistry is continuously evolving, driven by the increasing demand for efficient and commercially competitive ESS solutions. The total UK BESS market is expected to grow from less than 2GWh in 2022 to over 15GWh annually by 2030 (Figure 22). Grid scale BESS is expected to account for more than 50% of installed capacity in 2022 and is rising to 75% in 2030.

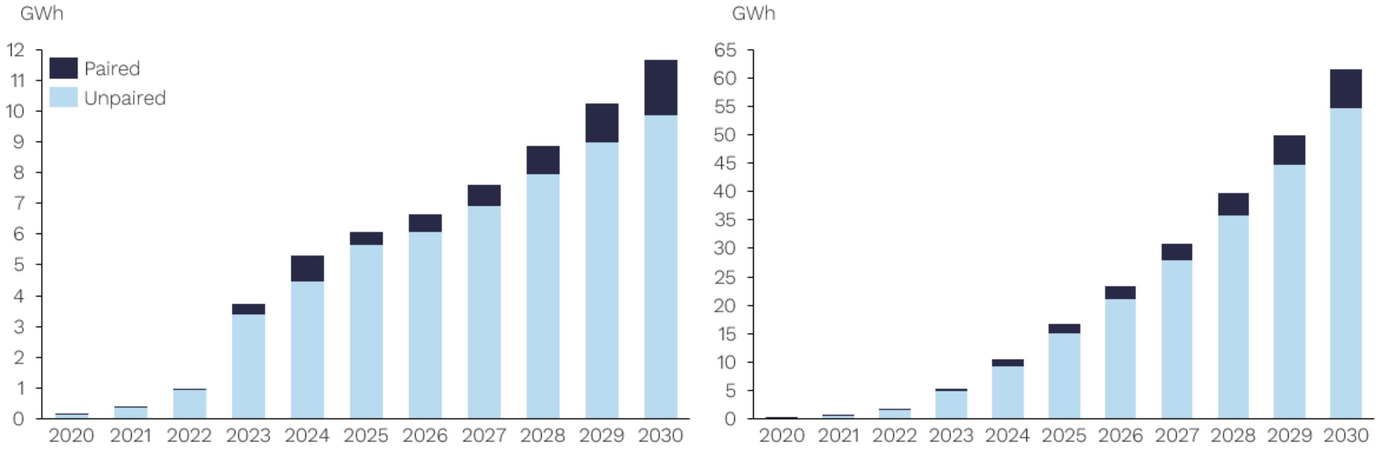
It is forecasted that the cumulative grid-scale BESS installed capacity by 2030 will reach 65GWh (Figure 23). This represents a substantial increase of around 60GWh installed capacity compared to 2022 figures. Furthermore, it is expected that non-renewable paired BESS applications will form the majority share of the installed capacity, accounting for around 90% by 2030. This is primarily driven by the increase in offshore wind, which is unsuited to pairing, but required for Net Zero.

Figure 22. UK BESS annual installed capacity in GWh by 2030



Source Rho Motion

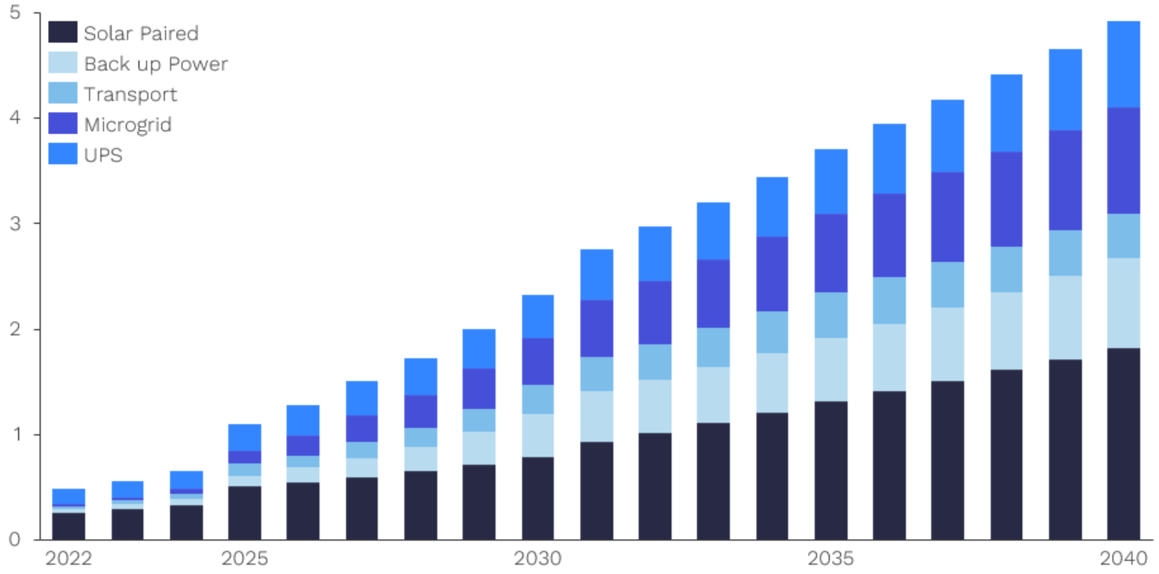
Figure 23. UK Grid Storage forecast, broken down by application (annual vs cumulative)



Source Rho Motion

Conversely, solar-paired installations are a key driver for the BTM market within the UK, constituting just under half of the market share by 2025, as depicted in Figure 24. Whilst this report focuses on grid-scale applications, it is important to note that BTM and grid-scale are not mutually exclusive. In particular, grid-scale storage (usually in the form of BESS) can be used in a 'behind-the-meter' manner, whereby a larger, renewable paired storage system, stores and utilises the energy generated on-site, thereby avoiding tax and other network-associated costs. This is a key feature that facilitates the development of dynamic business models, increasing commercial viability.

Figure 24. UK's BTM demand forecast, split by application



Source Rho Motion

As the UK energy networks continue to move toward their Net Zero targets, electricity generation will increasingly pivot toward more renewable and flexibility-orientated generation. As such, solar paired will continue to drive demand in BTM applications. Historically, the BTM market has featured a greater degree of lead-acid batteries. This is a legacy from earlier years, as lead-acid batteries were frequently used to form micro-grids and UPS. Lead acid is soon to be phased out as existing batteries are replaced by newer, more appropriate lithium-ion batteries. Currently, lithium-ion batteries are the battery technology of choice for solar-paired installations, forming over 90% of the BTM BESS due to a combination of affordability, performance, size and round-trip efficiency.

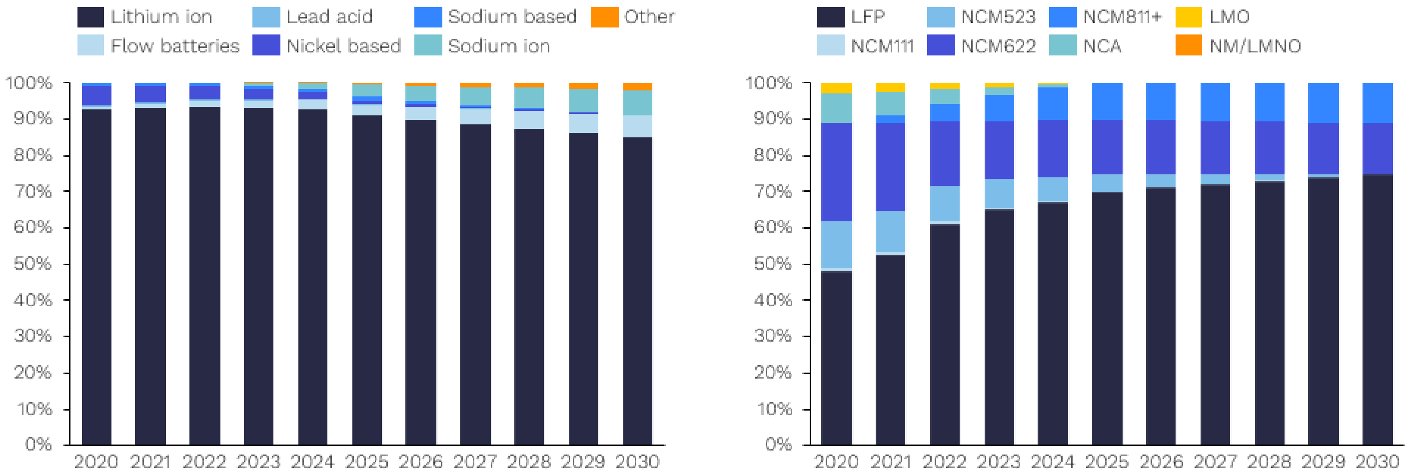
Influence of EV battery technologies on UK BESS

Grid BESS applications are expected to make up 62% of cumulative storage in both 2030 and 2040. North America has taken a leading role in lithium-ion battery deployment and although China has made progress across small-scale BESS applications, most growth is set to come from grid/utility-scale installations. As EV adoption becomes widespread, and demand increases for fast-charging infrastructure, so is the expected demand for grid-scale stationary storage applications.

Lithium-ion batteries are set to dominate the BESS landscape in the UK, as illustrated in Figure 25, accounting for approximately 90% of grid-scale installations and 80% when combined with BTM. Rho Motion's market projections indicate that lithium-ion batteries will maintain their majority market share, representing over 75% of the BESS market until 2040. Amongst lithium-ion batteries, there is widespread adoption of LFP, primarily due to its reduced cost and greater cyclability relative to higher nickel content chemistries. However, a diversification trend is anticipated as alternative technologies, such as flow batteries, mature over time.

Flow batteries are projected to make up around 6% of the total BESS market in the UK by 2040 and capture a higher share of grid-scale installations due to their unique advantages. Notably, Invinity Energy Systems, a prominent developer of redox flow BESS systems, has recently announced plans for widespread deployment of a 7MW/30MWh vanadium flow battery system, marking a milestone in the UK's grid-scale battery industry.

Figure 25. UK BESS technology landscape and lithium-ion chemistry split



Source Rho Motion

Another emerging battery technology, sodium-ion, is expected to start to capture market share in the UK from 2024, rising to over 7% by 2040. Sodium-ion batteries have a robust ability to retain energy when temperatures decrease.[12] This is especially relevant in northern parts of the UK, which are often a source of renewable energy generation, but experiences colder temperatures during the winter months.

Chinese developers have already begun scaling up sodium-ion cell production, while in the UK, companies such as Faradion and AMTE Power have been at the forefront of sodium-ion technology development. The collaboration between Faradion and AMTE has led to pilot-scale production and the successful creation of sodium-ion battery packs by AceOn, representing a significant milestone for sodium-ion batteries in the UK's BESS market.

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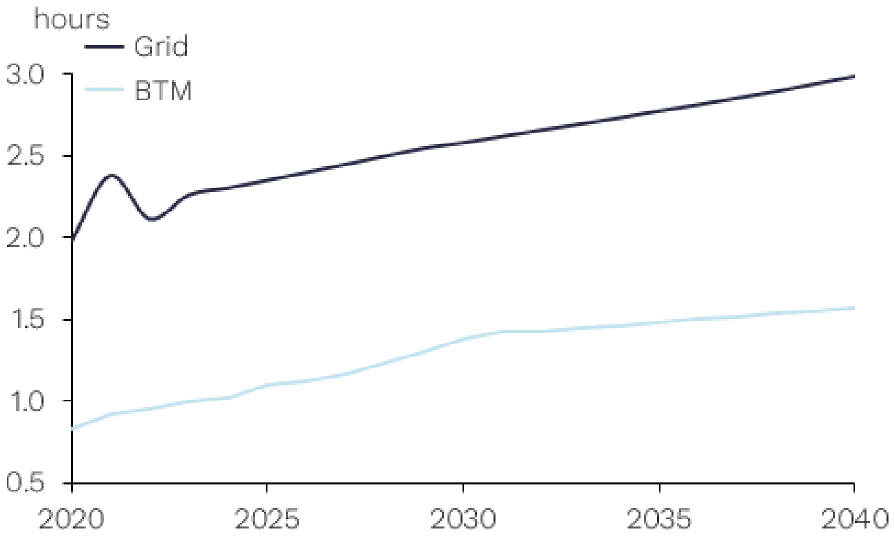
[12] Cleantechnica, 2023. The Sodium-ion battery is coming to production cars this year

Increased BESS storage duration is a key market trend

The global BESS market has experienced distinct regional trends, shedding light on the importance of storage duration as a key market indicator, as illustrated in Figure 26 and Figure 27). In 2021, there was a noticeable surge in the average grid storage duration worldwide, driven primarily by the strong growth observed in the North American market. However, this trend experienced a slight downturn in 2022 as China, known for its preference for shorter-duration projects, regained a larger market share. Notably, in recent months, China has made significant announcements, signalling their intention to incentivise developers to install BESS with extended durations of four hours, surpassing the conventional two-hour duration.

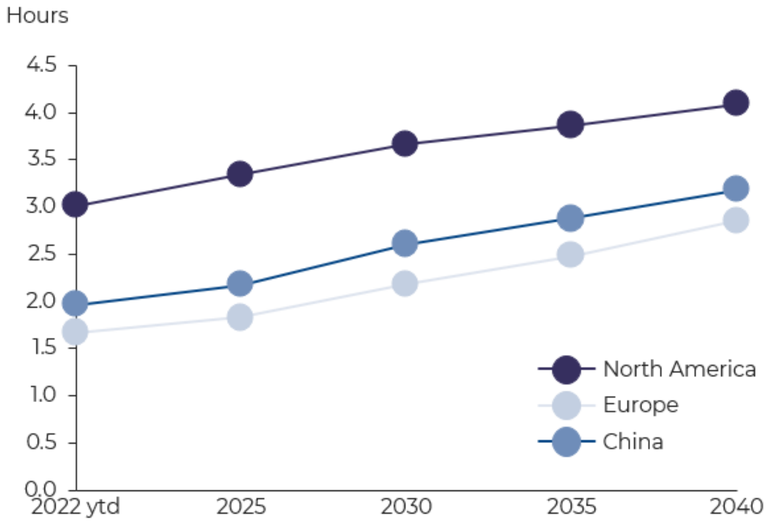
Conversely, shorter durations are more common in BTM BESS applications, largely due to the prevalence of UPS systems. These UPS systems typically operate for durations of less than one hour. However, it is anticipated that even in the BTM market, there will be a growing demand for longer storage durations.

Figure 26. Average global BESS storage duration by installation year



Source Rho Motion BESS Database

Figure 27. Average global BESS storage duration by region



Source Rho Motion BESS Database

UK government’s long-duration strategy

To accelerate the adoption of long-term duration, the UK government announced in June 2021 a GBP68 Million Longer Duration Energy Storage Demonstration Programme. The programme is intended to accelerate the commercialisation of technologies at either end of the maturity spectrum, covering technologies that are close to, or already at, commercial scale operations, as well as providing funding for ‘first-of-a-kind’ pilot projects to test and demonstrate their ability in helping the UK achieve Net Zero. Technologies involved in the programme to date include vanadium Redox flow batteries, compressed air energy storage as well as thermal storage technologies.

Additionally, the UK has committed to developing a long-term duration energy storage policy by the end of 2024.[13] This will primarily focus on outlining a stable and attractive revenue stream for investors and project operators, with policies such as a cap and floor mechanism being explored in early consultations. Securing suitable revenues is one of the major difficulties in incorporating long-term energy storage into the UK grid. Short-term storage batteries generate higher revenue the more they are cycled (charged and discharged). However, this revenue generation model does not apply to long-term energy storage systems which are not designed for frequent cycling. Alternative incentives will therefore need to be implemented to encourage the deployment and utilisation of long-term energy storage that has a lower usage/cycle rate.[14]

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[13] Parliamentary Office of Science and Technology (December 2022). Longer Duration Energy Storage.

[14] Crozier et al (2022) Modelling of the Ability of a Mixed Renewable Generation Electricity System with Storage.

5. Battery technology assessment for the UK grid

Introduction to the assessment

Battery technologies are expected to play a fundamental role in the future of the UK electricity grid as BESS developers seek ways to accommodate the dynamic requirements i.e., flexibility of the grid and to meet growing demand for high-performance low-cost alternatives to those already deployed.

The choice of energy storage technology ultimately depends on the specific grid flexibility application, cost, and performance requirements, but is broadly predicated on meeting the future needs of the UK grid with respect to energy security, reliability, sustainability, efficiency, and flexibility. As the demand for reliable, efficient, and sustainable BESS continues to grow, so does the requirement to enhance our understanding of the performance characteristics and advancements in battery technologies, such as enabling higher energy storage capacity, faster charging rates, longer lifespan, and enhanced safety features.

This section therefore examines the key performance of various existing and emerging battery technologies to provide an assessment of compatibility for the UK grid to 2040. The assessment focuses on the key performance characteristics, metrics, and compatibility of each electrochemical form (and their subsets),

Decision criteria and main drivers

The assessment is primarily focused on four main battery types and respective electrochemical forms (see Table 8), which are currently or expected to be deployed in energy stationary storage applications over the next decade. The assessment focuses on the following six key performance indicators, important to BESS and the UK's need for grid flexibility and stability:

Performance:

- Response time
- Cycle life
- Discharge duration
- Energy density
- Cycle life
- Safety

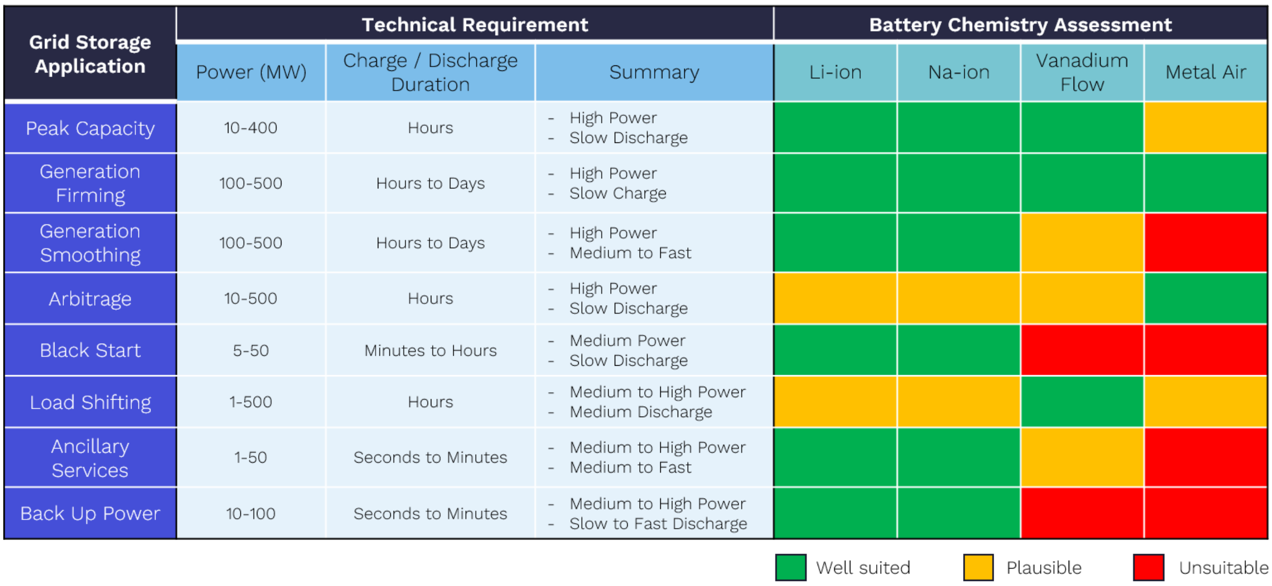
Table 8. Electrochemical forms in the assessment

Battery parent	Electrochemical forms (principal cathode)
Lithium-ion	• NMC – Lithium nickel cobalt manganese oxide • LFP – Lithium iron phosphate
Sodium-ion	• Prussian blue • Layered transition metal oxides • Polyanionic
Redox flow	• Vanadium • Zinc iron • Zinc bromine
Metal-air	• Metal-air

Battery suitability for each flexibility application

Lithium-ion and sodium-ion batteries are suitable for the broadest range of grid flexibility applications as they offer a high-energy and power solution, size, and fast response capabilities (see Table 9). Responsiveness is a key consideration when selecting a battery technology for applications such as backup power where access to the stored energy is required immediately.

Table 9. BESS suitability matrix: technical and application requirements



Grid Storage Application	Technical Requirement			Battery Chemistry Assessment			
	Power (MW)	Charge / Discharge Duration	Summary	Li-ion	Na-ion	Vanadium Flow	Metal Air
Peak Capacity	10-400	Hours	- High Power - Slow Discharge	🟩	🟩	🟩	🟨
Generation Firming	100-500	Hours to Days	- High Power - Slow Charge	🟩	🟩	🟩	🟩
Generation Smoothing	100-500	Hours to Days	- High Power - Medium to Fast	🟩	🟩	🟨	🟥
Arbitrage	10-500	Hours	- High Power - Slow Discharge	🟨	🟨	🟨	🟩
Black Start	5-50	Minutes to Hours	- Medium Power - Slow Discharge	🟩	🟩	🟥	🟥
Load Shifting	1-500	Hours	- Medium to High Power - Medium Discharge	🟨	🟨	🟩	🟨
Ancillary Services	1-50	Seconds to Minutes	- Medium to High Power - Medium to Fast	🟩	🟩	🟨	🟥
Back Up Power	10-100	Seconds to Minutes	- Medium to High Power - Slow to Fast Discharge	🟩	🟩	🟥	🟥

🟩 Well suited 🟨 Plausible 🟥 Unsuitable

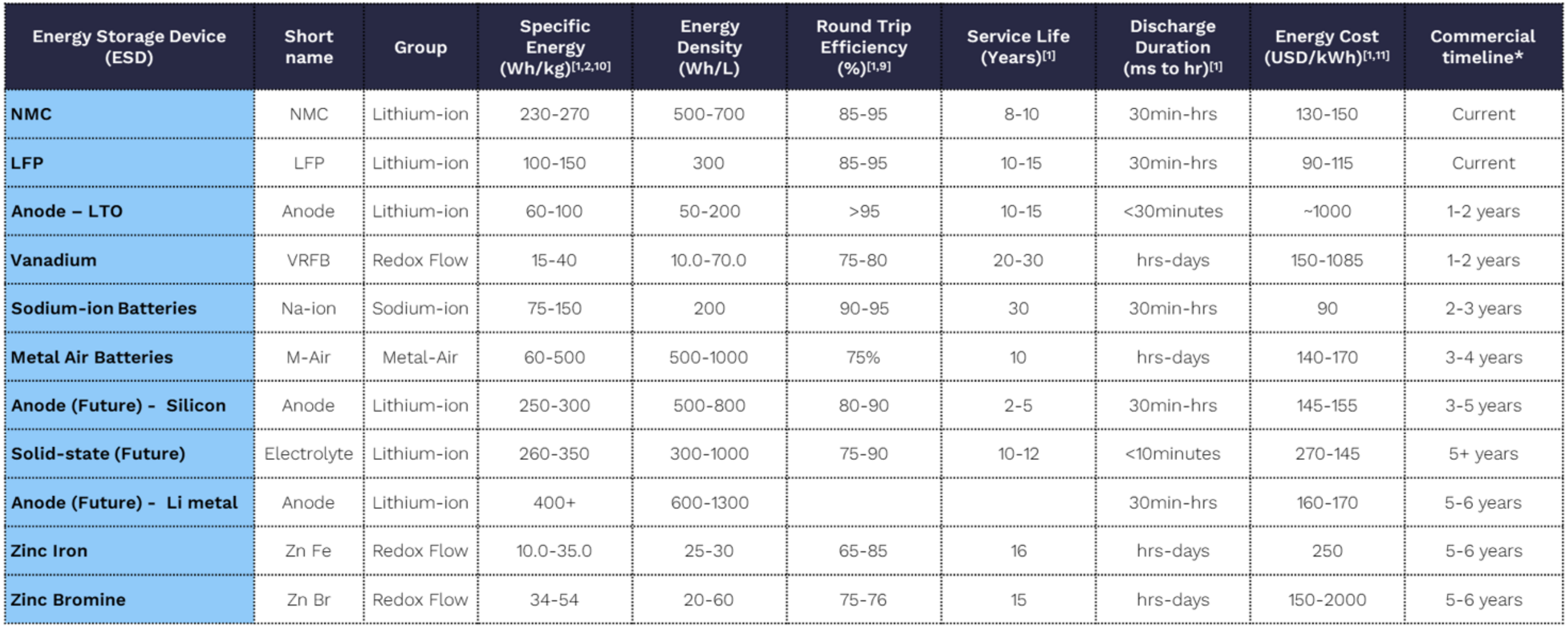
Source Kebebe, Kalogiannis, Mierlos [*Stationary energy storage devices for large scale renewable energy*]().

Vanadium flow batteries are ideally suited for generation firming, generation smoothing and load shifting applications as these applications typically require high power and longer duration charge/discharge cycles. Furthermore, vanadium flow batteries excel in providing steady and sustained power over extended periods. Their slower charge and discharge rates are well-suited for these applications, allowing for efficient energy management and grid stability.

Metal-air batteries are particularly well-suited for backup power applications as they possess high energy density, enabling them to deliver sustained power over extended periods. They exhibit slow to medium discharge rates, making them suitable for providing power during blackouts or emergencies. However, metal-air batteries may not be suitable for applications that require frequent charge and discharge cycles due to their limited cycle life compared to other battery chemistries. Therefore, they are not typically used for peak capacity, generation firming, generation smoothing, arbitrage, load shifting, or ancillary services.

Detailed performance metrics for each electrochemical form and their variants are shown in Table 10 and are covered in detail in the following section.

Table 10. Battery technology performance characteristics and commercialisation timeline



Energy Storage Device (ESD)	Short name	Group	Specific Energy (Wh/kg)[1,2,10]	Energy Density (Wh/L)	Round Trip Efficiency (%)[1,9]	Service Life (Years)[1]	Discharge Duration (ms to hr)[1]	Energy Cost (USD/kWh)[1,11]	Commercial timeline*
NMC	NMC	Lithium-ion	230-270	500-700	85-95	8-10	30min-hrs	130-150	Current
LFP	LFP	Lithium-ion	100-150	300	85-95	10-15	30min-hrs	90-115	Current
Anode – LTO	Anode	Lithium-ion	60-100	50-200	>95	10-15	<30minutes	~1000	1-2 years
Vanadium	VRFB	Redox Flow	15-40	10.0-70.0	75-80	20-30	hrs-days	150-1085	1-2 years
Sodium-ion Batteries	Na-ion	Sodium-ion	75-150	200	90-95	30	30min-hrs	90	2-3 years
Metal Air Batteries	M-Air	Metal-Air	60-500	500-1000	75%	10	hrs-days	140-170	3-4 years
Anode (Future) - Silicon	Anode	Lithium-ion	250-300	500-800	80-90	2-5	30min-hrs	145-155	3-5 years
Solid-state (Future)	Electrolyte	Lithium-ion	260-350	300-1000	75-90	10-12	<10minutes	270-145	5+ years
Anode (Future) - Li metal	Anode	Lithium-ion	400+	600-1300			30min-hrs	160-170	5-6 years
Zinc Iron	Zn Fe	Redox Flow	10.0-35.0	25-30	65-85	16	hrs-days	250	5-6 years
Zinc Bromine	Zn Br	Redox Flow	34-54	20-60	75-76	15	hrs-days	150-2000	5-6 years

*Commercial timeline denotes when the battery technology is expected to be widely available

Source Rho Motion

Key performance characteristics

Discharge and storage duration

Discharge duration is a critical KPI for assessing the suitability of BESS technologies for different grid flexibility applications. This refers to the length of time that stored energy can be continuously discharged from a BESS system at its power capacity before the energy capacity is fully depleted (e.g. 1 MW battery that has a discharge time of five hours can provide 5 MWh of energy).

On the other hand, storage duration is closely linked to the ability of different technologies to retain a charge over time, known as self-discharge, as this can significantly impact energy storage effectiveness. If a battery experiences significant charge loss due to self-discharge, it becomes impractical for long-term energy storage purposes, and therefore, minimising self-discharge is important for BESS.

Lithium-ion and sodium-ion batteries, while widely used and versatile, demonstrate relatively short self-discharge rates in the order of minutes to hours (Table 11). Within the first 24 hours, these batteries typically lose around 5% of their charge due to self-discharge, followed by a monthly self-discharge rate of anywhere between 0.5% to 3%. Consequently, these technologies may not be suitable for multi-day and extended storage durations.

In contrast, redox flow batteries exhibit promising capabilities for ESS lasting from hours to days, and potentially even months in seasonal storage applications. The distinct design of redox flow batteries, with separate electrolyte tanks that do not interact with each other, allows for a self-discharge rate close to 0%. Similarly, metal-air batteries, particularly non-aqueous systems, offer the potential to minimise self-discharge.

Table 11. Main performance characteristics of key electrochemical forms in grid-scale energy storage applications

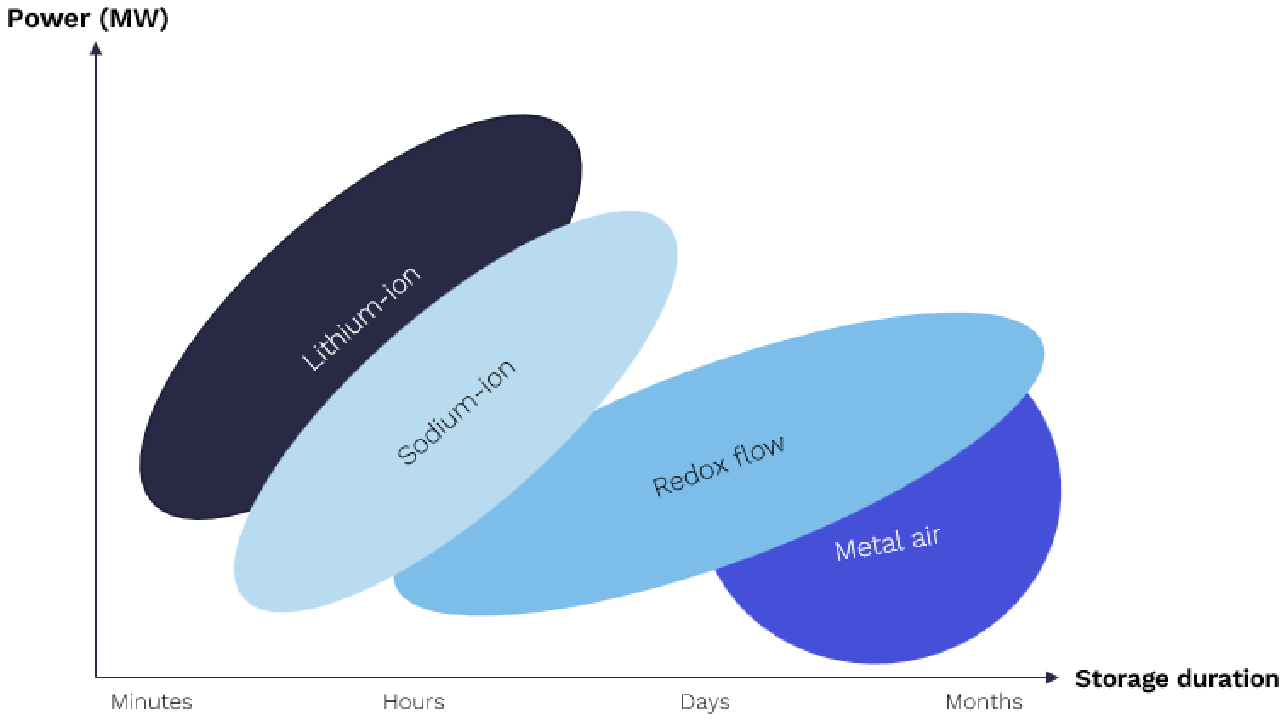
Battery Type	Response time	Discharge duration	Round-trip efficiency
Lithium-ion	Instant	Minutes – hours	High
Sodium-ion	Instant	Minutes – hours	High
Redox flow	Slow	Hours – days	Moderate
Metal-air	Fast	Hours – days	Moderate

Source Rho Motion

Power

Power capability is an important KPI in applications where rapid response is required, such as UPS. The applicability of various electrochemical forms for grid flexibility applications is enhanced when considering both the power rating and discharge duration needs, as shown in Figure 28. Here, both lithium-ion and sodium-ion are highly suitable across multiple grid flexibility applications and plausible for load shifting and arbitrage greater power capability, while vanadium flow is also applicable or highly plausible across most applications, with the exception of backup power due to its relatively lower power capability and longer discharge duration.

Figure 28. BESS landscape as a function of storage duration and power rating



Source Rho Motion

In lithium-ion, LFP is less tolerant to faster charge/discharge rates due to its greater resistivity than NMC. This can induce ‘knee points’, which is a sudden drop in the performance and cause of accelerated degradation. In most lithium-ion batteries, the principal anode active material is graphite, which is not designed to work effectively at discharge rates above 2C, due to an increased occurrence of irreversible side reactions including lithium plating.[15]

Some alternative anode materials that exhibit greater power capabilities include LTO and niobium-based materials. LTO offers a higher power density than graphite, enabling superior fast-charge and discharge capabilities, where it is capable of a maximum charge rate of 5C. This attribute can be advantageous in applications that require swift response times, such as backup power systems.

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[15] Xu, W. et al 2022, Exploring the limits of the rapid-charging performance of graphite as the anode in Lithium-ion batteries.

Niobium oxide materials offer similar benefits to LTO in terms of stability and fast-charging capabilities, but they are significantly more energy dense – up to 2x more. Similarly to LTO, Niobium oxide anodes can achieve discharge rates up to 10C and have a safe operational voltage. The chemistry of these Niobium oxide materials can vary between developers; Nyobolt has developed a niobium tungsten oxide material, whereas Toshiba has a Niobium Titanium Oxide, and Echion has a mixed niobium oxide (XNO®) where the additional metal is not disclosed. Therefore, while niobium itself is not expensive (~US$40/kg), the cost associated with other metals used in the oxide complex will vary significantly. Additionally, these niobium anode materials are still in the early stages of development, with barriers to be overcome prior to commercialisation.

Sodium-ion, on the other hand, has superior power performance due to its greater conductivity. Sodium-ions can achieve faster C-rates than lithium-ions when utilising the same concentration of electrolyte.

Flow batteries are different from lithium-ion and sodium-ion batteries because both power and energy storage capacity can be controlled separately, and therefore power does not come at the expense of energy density. In this case, energy storage capacity is controlled by the volume and concentration of the electrolytes and power density is controlled by the number of cells in the central stack.

The power performances of metal-air chemistries are generally poor and more suited to slow and long charge and discharging speeds. For example, Form Energy's iron-air system has a charge and discharge duration of 100 hours. This makes the technology favourable for long-duration applications but not for those where fast response is required, like ancillary services.

Cycle life

One of the most important KPIs within BESS technologies is cycle life. An ESS system is generally expected to meet a lifetime requirement of more than 3000 cycles or around 10-15 years.

LFP exhibits a longer cycle life, capable of over 2,000 cycles compared to around 1,000 cycles for NMC under standard conditions. By implementing optimised cycling conditions, LFP's cycle life can be extended up to 5,000 cycles. These conditions include limiting the depth of discharge, reducing the operational voltage window and optimising thermal management. Its higher round-trip efficiency of around 92% to 95% results in lower energy loss per cycle, which is important for the preservation of service life.

Most lithium-ion batteries contain a graphite anode, which exhibits good cycle life, but less so than lithium titanate oxide (LTO). LTO demonstrates exceptional stability during the insertion and extraction of ions during charge and discharge cycles, allowing for a potential 100% depth of discharge (DoD). Additionally, LTO experiences less degrading side reactions due to its higher activation overpotentials of these reactions, which helps contribute to a longer cycle life in comparison to graphite.

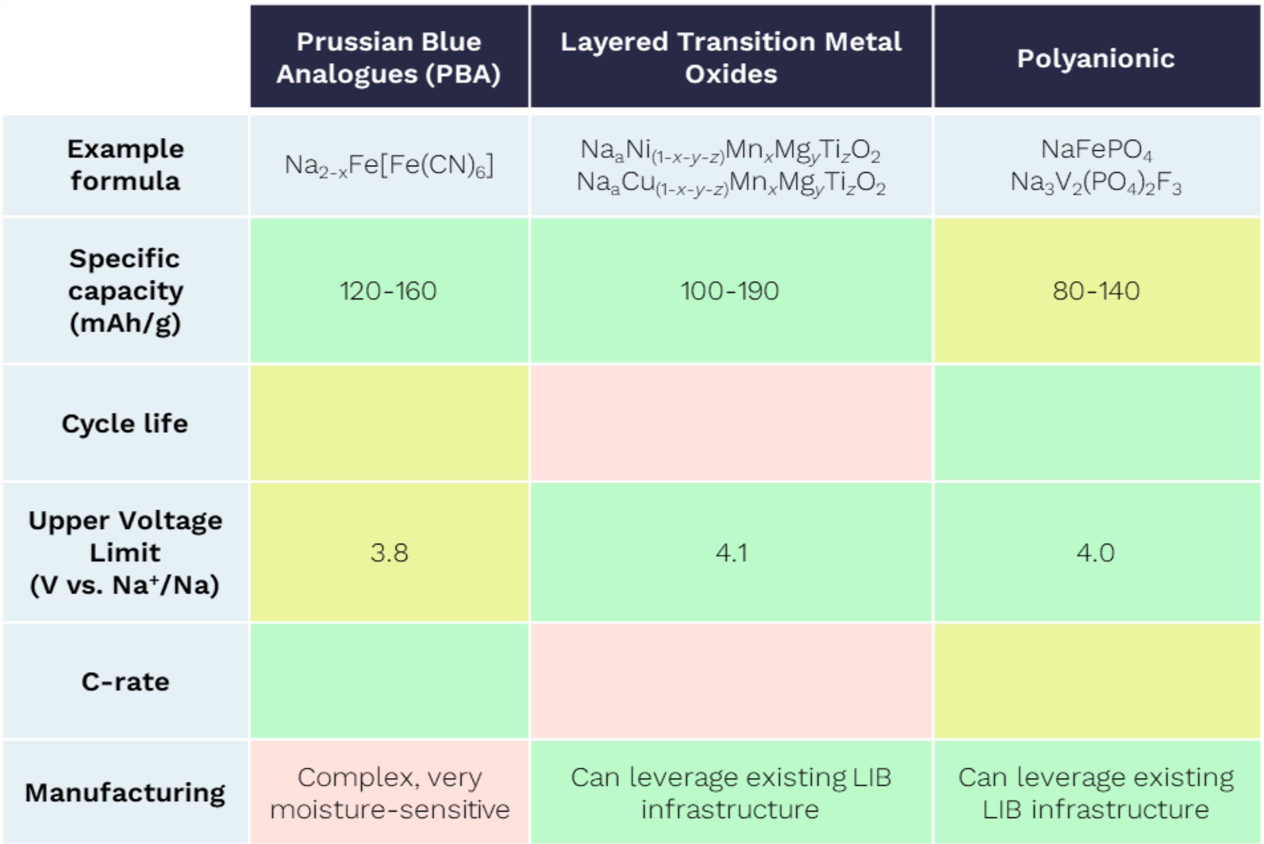
Most sodium-ion cells currently under development employ oxide cathode materials; either prismatic (P-type) or octahedral (O-type) layered crystal structures like those used in established lithium-ion NMC technology. The type and proportions of different metals used in sodium-ion layered oxides have a profound effect on performance according to the crystal structure they are organised into.

One drawback of sodium-ion is its poorer cycling stability due to the disruptive nature of sodium-ions on the layered cathode structure during insertion and extraction. Prussian Blue Analogues (PBAs) and polyanionic materials exhibit greater stability by utilising a three-dimensional network within their crystal structure (see Table 12.) This network facilitates the movement of sodium-ions within the cathode, improving stability and ionic conductivity, albeit at the expense of energy density.

Sodium-ions are incompatible with graphite anodes in traditional electrolyte systems, necessitating the use of alternative materials. Currently, hard carbon is the main anode material employed in sodium-ion batteries, representing high storage capacity and cycling stability. Hard carbon differs from graphite in its more disordered carbon layers, creating larger void spaces that can accommodate sodium-ion storage more efficiently.

Redox flow batteries have emerged as a potential option to extend the number of cycles to a service life that could exceed 30+ years under normal operating conditions. These batteries utilise separate electrolyte solutions stored in external tanks, allowing for scalable energy storage capacity and seamless replenishment of both the electrolyte solutions stored in external tanks and the central cell stack.

Table 12. Characteristics of three main Na-ion cathode types under development



	Prussian Blue Analogues (PBA)	**Layered Transition Metal Oxides**	**Polyanionic**
Example formula	$Na_{2-x}Fe[Fe(CN)_6]$	$Na_aNi_{(1-x-y-z)}Mn_xMg_yTi_zO_2$ $Na_aCu_{(1-x-y-z)}Mn_xMg_yTi_zO_2$	$NaFePO_4$ $Na_3V_2(PO_4)_2F_3$
Specific capacity (mAh/g)	120-160	100-190	80-140
Cycle life	🟨	🟥	🟩
Upper Voltage Limit (V vs. Na^+/Na)	3.8	4.1	4.0
C-rate	🟩	🟥	🟨
Manufacturing	Complex, very moisture-sensitive	Can leverage existing LIB infrastructure	Can leverage existing LIB infrastructure

Source Rho Motion

Flow batteries can also perform ‘deep cycles’ where charge and discharge durations can be several hours; which is not possible with lithium-ion batteries. Additionally, they can be used to store collected energy for extended periods by placing the system in ‘offline mode’ where the electrolyte tanks are disconnected to prevent flow into the cell stack. This causes the system to experience almost 0% self-discharging, whereas when left operational most redox flow systems can experience self-discharge rates as high as 20% per day.

Metal-air technology holds promise as a performance alternative to lithium-ion batteries, particularly for long-term storage applications. Various metals, including lithium, sodium, zinc, aluminium, and iron, have been explored for use in metal-air configurations. However, current metal-air technologies face challenges in achieving reversibility (limited to 1-5 cycles before anode replacement) and exhibiting relatively poor round-trip efficiencies of less than 65% in practical applications. Moreover, these systems typically operate with pure oxygen instead of ambient air due to contaminants that can degrade the metal anode. To achieve commercial viability, metal-air batteries must operate without the need for an air tank. Extensive research is being conducted to develop catalysts that facilitate the reaction with ambient air, converting it to pure O_2 for use in the metal-air system, removing the need to have a pure O_2 tank.

The start-up company Form Energy has made commercial advancements in metal-air batteries for ESS applications, particularly with their iron-air system. Iron-air configurations have lower energy density compared to metals like lithium and round-trip efficiencies of around 40%. As a result, this chemistry is better suited for long-term storage applications rather than regular cycling. Form Energy claims their systems can achieve discharge times of 100-150 hours, making them suitable for energy balancing services over months.

Energy density

While gravimetric energy density may be a less critical requirement in ESS than EV applications, volumetric energy density is crucial for space-efficient installations, especially when considering pairing with renewable energy sources like solar panels.

NMC, while highly applicable in EV applications that require longer range through its favourable energy density characteristics, comes at the expense of thermal stability and cycle life. LFP, on the other hand, has an intrinsically lower energy density (maximum achievable 170mAh/g) and was originally developed to be a safer, cheaper alternative with greater longevity to NMC, but at the sacrifice of energy density, thus making it a more favourable choice for BESS developers.

Generally, battery cell technology developments in the EV space are allowing developers in ESS to experience a ‘piggyback’ effect from EV production. This means the current and next-generation innovations are likely to come from the anode and electrolyte, with the goal of improving energy density, cycle life and safety.

Graphite, the incumbent anode active material, has performance limitations in EV applications, notably its specific capacity of 372mAh/g, but this is less of an issue in BESS applications. It does, however, have moderate fast-charging capabilities which are suitable for both EV and grid storage. LTO, which has lower energy density, improves charging capability and lifetime due to greater electrochemical stability; two requisites for grid flexibility applications. However, it is also significantly more expensive than graphite because it is heavier and less energy dense, thus less widely deployed than graphite in cells.

Silicon has been of significant interest in the lithium-ion battery space as a next-generation anode material. The main benefit of silicon is that it has the potential to give ten times the energy density of graphite, and therefore raises the prospect of significantly thinner electrodes. However, silicon is prone to swelling during charging and has relatively poor conductivity. Upon full lithiation, silicon expands by over 300% which pulverises the cell. As a result, developers have been working on several ways to mitigate this issue. Some of these include nanosizing, nano-structuring and the creation of carbon composite materials. All these methods aim to contain the expansion at the material level, preventing the overall bulk electrode and, consequently, the cell, from experiencing such drastic levels of expansion. The introduction of carbon material and/or the nanosizing of silicon material also helps to improve the conductivity of the bulk material, utilising the electronically conducting properties of some carbons and the increased surface area from nanosizing.

Silicon materials are far better suited to higher energy demand applications such as high performance EVs, where we are already seeing silicon being used as an additive in graphite-dominant anodes. Due to the advanced material engineering required to make silicon perform well in the cell, these materials will likely be expensive, especially initially as scaled production is only just beginning.

Lithium metal is being explored as a long-term alternative for high-performance EVs and other mobility applications, such as off-highway vehicles, because of its energy and power density, both of which are greater than silicon. While lithium metal has the potential to radically optimise cell design through its higher energy density, its development pathway is longer than silicon. In particular, it is incompatible with traditional cell architectures and must overcome technical challenges associated with manufacturing, such as rolling thin sheets of lithium metal. Currently, the applicability of lithium metal in the BESS market is limited, but it could provide an interesting alternative in grid applications that require fast charge/discharge, eliminating the need for power applications such as supercapacitors.

Current commercial metal-air technologies have relatively low energy densities, however, those that are under development have the potential to utilise a variety of pure metal anode materials, such as lithium metal.

Lastly, flow battery systems have low energy density due to the large amounts of electrolyte required for operation. These systems also require motorised pumps to move the electrolyte around the system, which limits the energy density at a system level.

Safety performance

Battery safety is determined by structural stability, operational temperature, and thermal runaway susceptibility, which can be impacted by different stressors such as extreme temperature.

LFP is inherently safer than NMC. It ignites at a higher temperature, does not easily release gases such as oxygen, and releases less heat in the case of battery malfunction/damage, reducing the risk of fire. The increased safety of LFP allows for higher cell-to-pack efficiencies, reducing the need for extensive thermal management. This results in space and weight savings, contributing to improved volumetric and gravimetric energy densities at the pack level. LFP does, however, exhibit inferior low-temperature performance compared to NMC chemistries. For instance, at -20°C, LFP loses approximately 45% of their initial capacity compared to 30% for NMC.

Sodium-ion is safer than lithium-ion because of its increased stability. The stability allows cells to be stored in a fully discharged state, meaning storage and transportation of sodium-ion cells can be performed more easily. Additionally, it has been observed that sodium-ion is thought to be less prone to thermal runaway than lithium-ion, due to a slower heating rate, which gives more time for heat to dissipate, reducing the effect on surrounding cells in the pack.

All redox flow batteries are inherently safer than lithium-ion because they are less susceptible to failure or short-circuit, which lowers the risk of fire. The main safety consideration for redox flow is the leakage of electrolytes and the formation of gases from side reactions within the system. The severity of these events will be highly dependent on the chemistry of the electrolyte used.

Metal-air batteries are also intrinsically safer than lithium-ion, primarily because non-flammable aqueous electrolytes, like potassium hydroxide (KOH), are used.

6. Impact of battery cost on BESS economic viability

Cell cost methodology

This section provides a cost assessment of selected battery cell technologies. The assessment analyses their relative competitiveness on a cost per kWh basis and compares this against key performance attributes to understand the applicability across different flexibility applications.

Drawing from Rho Motion's *Battery Cell Cost Model*, the cost stacks of lithium-ion and sodium-ion cells were analysed based on primary data collected from multiple industry analogues. This included stoichiometry, average voltage, capacity, energy, mass, volume, and cost data. Redox flow and metal-air cells, on the other hand, were based on top-down methodology using open-source data and industry insights given the limited information available.

Top-down assessment of cost

Storage duration versus cost comparison

Understanding the cost of battery technology in terms of cost per kWh and its relationship to storage duration is crucial for assessing the economic viability and competitiveness of BESS solutions. The cost per kWh directly impacts the overall project economics, influencing investment decisions and the potential for widespread adoption of energy storage technologies.

Moreover, storage duration plays a significant role in determining the appropriate technology for specific applications. Therefore, NMC and LFP are the preferred choices across storage durations of up to 10 hours, as depicted in Figure 29[16]. These lithium-ion chemistries have been extensively deployed and have achieved economies of scale, resulting in relatively lower costs per kWh compared to other technologies. However, storage durations exceeding four hours are also emerging as cost-competitive options. As discussed in previous sections, flow batteries (e.g. vanadium flow batteries) can store energy for extended periods without significant degradation, making them particularly suitable for applications requiring storage durations above four hours.

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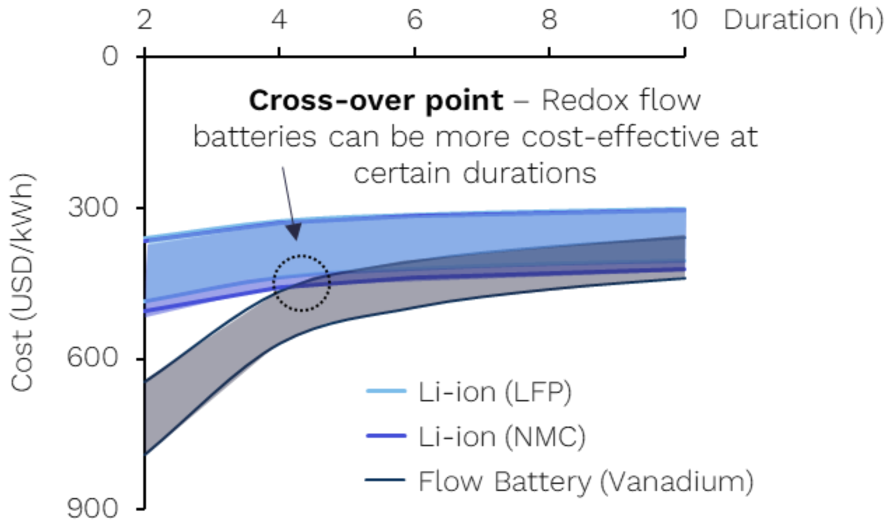
[16] Pacific Northwest National Laboratory (PNNL), 2020.

Figure 29. Levelised cost of storage duration curve



Source *Pacific Northwest National Laboratory (PNNL), 2020*.

In terms of total ESS costs, the key metric to optimise is cost per kWh and cost per charge/discharge cycle, also known as the levelised cost of storage (LCOS). To enhance the cost assessment and evaluate the benefit of installing energy storage solutions, the LCOS can be calculated to compare lithium-ion and other electrochemical forms, whereby costs (e.g., fixed, variable, direct, and indirect) are divided by energy delivered (i.e., accounting for roundtrip efficiency).[17] As illustrated in Figure 29, lithium-ion batteries may not be the ideal solution depending on the required storage duration, and other forms of electrochemical energy storage should be considered.

Life cycle costs

Another important cost variable in assessing overall BESS economic feasibility and sustainability is Life Cycle Cost (LCC). This measures the total lifetime costs of a project and encompasses not only the upfront investment in procuring the battery system (CAPEX) but also the operational and maintenance expenses (OPEX) over its entire lifespan. This differs from LCOS, which specifically focuses on the cost of producing electricity. LCOS is often used to compare the cost efficiency of different energy sources in generating electricity.

LFP batteries demonstrate longer cycle life and durability compared to NMC batteries which can contribute to lower replacement and maintenance costs over time. They are often considered cost-effective for shorter storage durations, typically up to four to six hours, due to their lower upfront costs and relatively stable performance. The LCC is illustrated in Figure 30 for a 15-year LCC user.

NMC batteries, on the other hand, offer higher energy density and power capability, which can be advantageous for applications requiring longer storage durations. While NMC batteries may have higher initial costs compared to LFP, their energy storage

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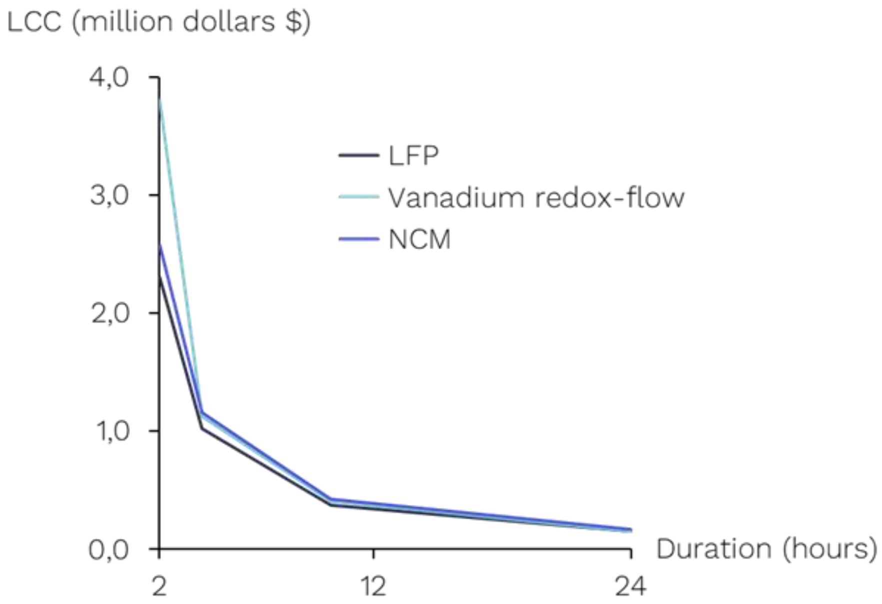
[17] O. Schmidt et al., 2018, Projecting the Future Levelised Cost of Electricity Storage Technologies.

capacity makes them potentially more LCC cost-effective for storage durations beyond four to six hours, depending on specific project requirements and economic factors.

Vanadium flow batteries have the unique advantage of decoupling power and energy, making them suitable for longer storage durations, typically ranging from four to twelve hours and greater. Vanadium flow batteries have higher initial costs compared to lithium-ion chemistries, primarily due to the cost of vanadium electrolyte, but their long lifespan and the ability to recycle and reuse vanadium can contribute to their cost-effectiveness in the long run.

Figure 30. Life cycle cost (LCC) of different BESS installations at different durations, considering a 10MW installation

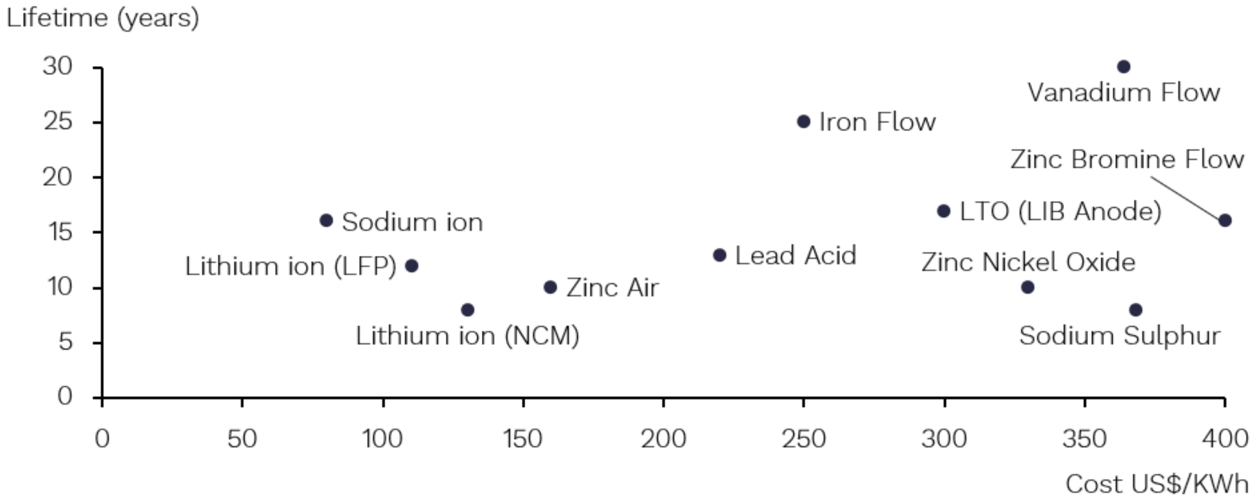


Source [*Pacific Northwest National Laboratory (PNNL), 2020*](.).

A comparison of the typical lifetime versus the cost of different types of batteries used in energy storage (Figure 31) along with how far along (in terms of years) each technology is on its journey to commercialisation (Figure 32) provides an illustration of the potential pathway for cost optimisation for current and next-generation technologies.

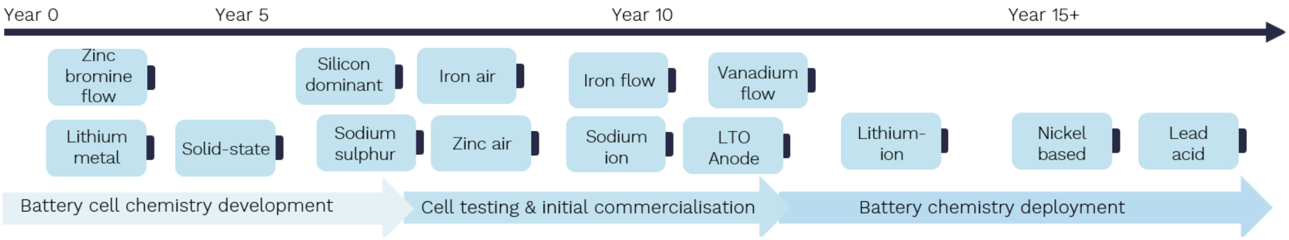
The cost of energy storage technologies is highly dependent on the specific application and location. Factors such as grid capacity, project size, technological advancements, raw material availability, manufacturing efficiencies, and environmental conditions can all affect the overall cost of a project. Therefore, it is crucial to carefully evaluate the costs and benefits of each energy storage technology on a case-by-case basis according to the ongoing advancements and market developments to determine the most suitable option for a given application.

Figure 31. Battery lifetime to unit cost



Source Rho Motion

Figure 32. Timeline to commercialisation for battery cell technologies



Source Rho Motion

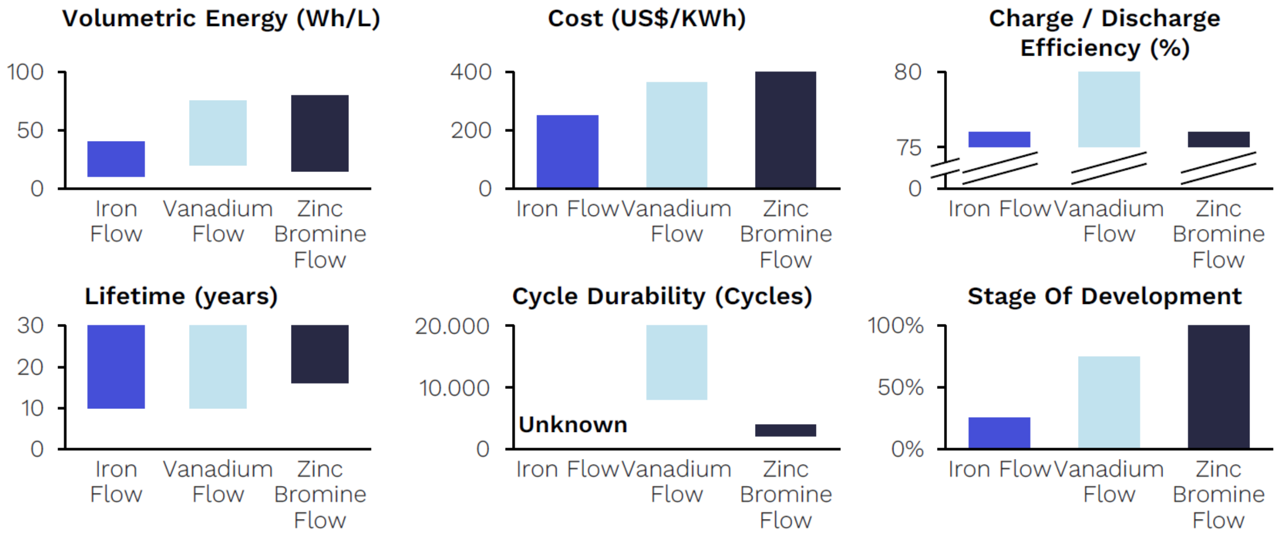
Redox flow batteries cost and implications

Flow batteries have the potential to become cost competitive but are currently significantly costlier on a per kWh-basis than other electrochemical forms, such as lithium-ion and sodium-ion. However, economies of scale have yet to be realised across all major redox flow battery forms, with costs currently in the range of US$200-400/kWh, as illustrated in Figure 33. This applies to projects that are already deployed, for example, vanadium flow saw 654MWh of projects come online in 2022, while zinc-bromine flow saw the trial production of an early-stage project in China at 4.5GWh capacity. The cost of vanadium, however, is a potential roadblock, given the large electrolyte volumes required for scaled projects.

Zinc is a significantly cheaper option, and even cheaper for zinc-iron. However, both zinc chemistries struggle with cycle life due to the tendency to form zinc dendrites which lead to a short circuit of the battery cell. This means that more investment is needed in installing enablers to prevent this, including more advanced membrane materials and more stable solid electrodes in the cell.

While flow batteries have clear advantages across many key metrics, commercial uptake has not yet occurred.

Figure 33. Performance and cost ranges of Redox flow battery forms



Source Rho Motion analysis

Metal-air batteries cost and implications

Metal-air batteries use a pure metal anode material and have ambient air acting as the cathode material. These have the potential to have good applications in long-term storage, where they are cheaper and more efficient than alternatives like lithium-ion. Pure metal anodes also have greater specific capacity and energy density than that of lithium-ion batteries.

A significant cost drawback of metal-air technologies is the difficulty in making the reaction reversible. Most of the different types of metal-air configurations can only perform one to five cycles before the metal anodes need to be replaced.

One of the cost benefits of metal-air is that it requires only one electrode. The use of cheaper and more abundant materials for energy storage systems becomes increasingly attractive as greater strain is placed on the lithium-ion supply chain because of the burgeoning EV market. However, from a cost production perspective, lithium metal does not seem viable considering it has a huge excess of lithium, thus would likely need a current collector to mitigate.

Bottom-up cost model assumptions for lithium-ion and sodium-ion technologies

Model data inputs included cell composition, cell technical specifications, material prices and production facility settings (Table 13.) Data outputs included

- Performance metrics such as energy density (Wh/L), specific energy (Wh/kg), electrode characteristics
- Cost metrics such as capital expenses (e.g., capital equipment, building, land, utilities, working capital, and launch costs)
- Operating expenses comprising fixed costs (e.g., general, sales and admin, research and development, and depreciation)
- Variable costs (e.g., materials and purchased items, direct labour, electricity, production costs, and variable overheads).
- Cost calculated on an energy basis, such as opex, material cost (both in US$/kWh) and capital intensity (in MMUS$/GWh/yr).

The cost model assumed a production facility located in the UK with a capacity of 10GWh/yr and an average plant energy requirement of 52kWh per kWh of cell. Cells were assumed to be fully maximised i.e., large pouch format with a volume of 409cm^3. A detailed summary of the specific cell component choices and modelled scenarios can be found in *Annex I.*

Firstly, a few baseline scenarios were modelled, indicative of present day battery cells; cathodes included NMC811 and LFP paired with either graphite or graphite-SiO (assumed ~5% Si) anode and liquid electrolyte. Then, to show the cost and performance evolution of various lithium-ion technologies, the same cathodes against various next-generation anode and electrolyte pairings were modelled, including silicon-dominant and lithium-metal anodes and solid-state electrolytes, principally sulphides, oxides and polymers. Next-generation technologies were defined as those under development and ready for commercialisation in the next 3-10 years.

Table 13. Cost model data inputs and outputs

Model specification	Model data input	Model data output
Cell composition	Cathode, anode, electrolyte, anode pre-lithiation	Energy density, specific capacity
Solid electrolyte	Separator thickness, catholyte content of cathode	Electrode characteristics e.g., mass loading, press density
Cell technical specs	Cathode loading, N/P ratio	
Material prices	CAM, anode active material & lithiation, electrolyte, additives	Energy basis: Capex intensity (GWh/yr), Opex, revenue, material costs ($/kWh), material intensity (kg/kWh) Plant Capex ($), revenue ($/yr) & Opex ($/yr)
Facility settings	Production capacity (GWh/yr), markup (% total Opex), country, plant energy requirement (kWh/cell)	

Bottom-up cost results

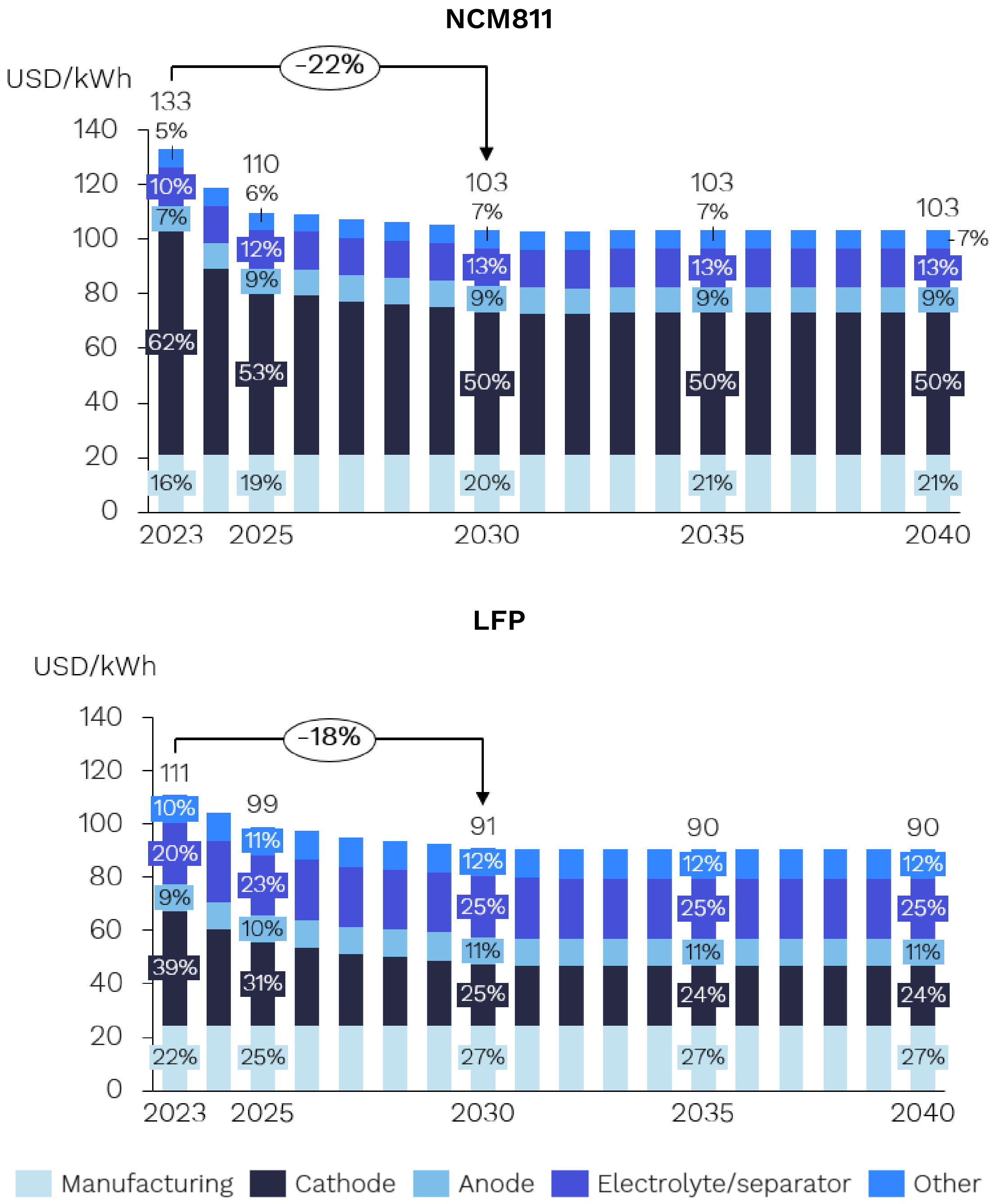
The cost stack for lithium-ion and sodium-ion cell technologies was assessed on a time series projected through to 2035. This incorporated different combinations of cathode, anode and electrolyte formulations, as well as the prevailing price of battery-grade active materials. To that end, the cost of active materials was analysed according to prevailing current and future market prices, indexed as of Q2 2023 in real terms[18], while the competitiveness of each technology was determined by cross-examination of the key performance characteristics versus cost on a per unit basis.

Main cost contributors of lithium-ion

The main cost contributor in lithium-ion is the bill of materials, principally cathode active materials, followed by processing-related costs, as shown in Figure 34. This cost is expected to decrease in the long-term, which will translate to a cost reduction of 22% and 18% for NMC811 and LFP in 2030 respectively. The main driver for the cost reduction is linked to the anticipated market equilibrium for each of the principal battery-grade materials (e.g., Li, Ni, Co, Mn, C) which will be reached at varying times during the 2025 to 2032 period.

[18,16] Source: Benchmark Mineral Intelligence Battery-Grade Price Index, as of Q2 2023.

Figure 34. Cost stack outlook for NCM811 and LFP, base case – current to 2040*


NCM811

LFP

Source Rho Motion Cell Cost Model

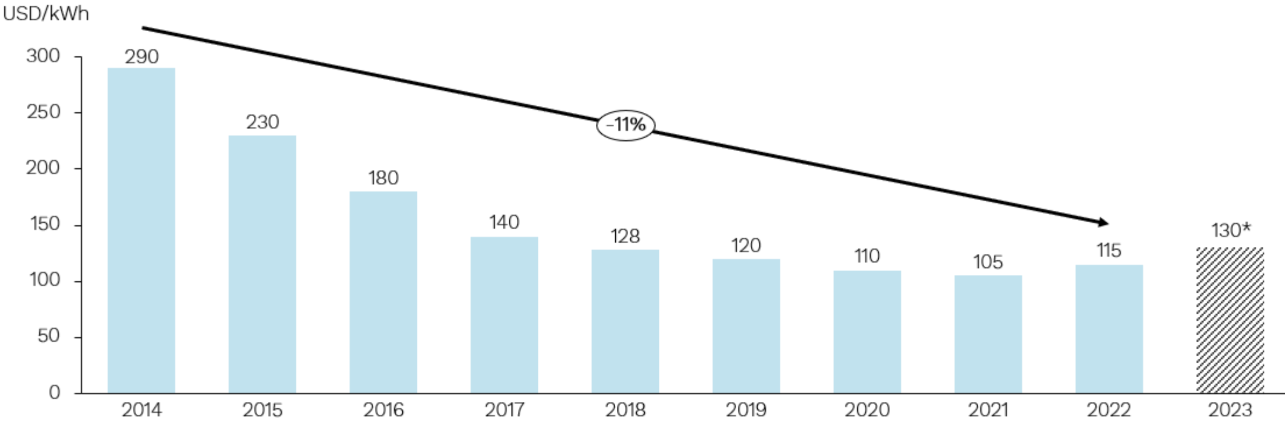
**Cost model assumptions*

- *Present day and future scenario Liquid electrolyte, C-Si anode (5% blend of Si additive); representative of state-of-the-art cells for EV*
- *Plant capacity of 10GWh/yr, UK-based.*

Battery cell costs increased in 2022 for the first time in the last decade, as illustrated in Figure 35. This was mostly driven by a significant rise in metal prices for key battery metals and their chemical forms, particularly lithium carbonate (LiCO3) and hydroxide (LiOH-H2O), which saw a 400% price increase from Q1 2021 to Q1 2022.[16] Other battery-grade materials have also experienced price rises, including nickel sulphate, cobalt sulphate, high-purity manganese monohydrate (HPMSM), phosphorous, iron, and copper.[19]

The reasons behind these cost increases can be attributed to short-term sentiment-driven pricing mechanisms, geopolitical factors, the Covid-19 pandemic, and supply bottlenecks stemming from fluctuations in Chinese production. In the mid-term, i.e., 2025-2032, raw material pricing is expected to be determined by supply-demand balances, while in the long-term i.e., 2033 and beyond, this will be driven by incentivised pricing for metal suppliers. As a result, the market is expected to balance from 2033, and stable raw material prices are expected to ensue.

Figure 35. Lithium-ion battery cell costs, weighted average – 2014-2023*



**Values are based on large contract orders in EV.*

Source Rho Motion and Benchmark Mineral Intelligence

The impact of rising metal prices on the bill of materials (BoM) for lithium-ion chemistries extends to lithium-ion technologies utilised in BESS applications.[20] Notably, the analysis of cell cost models reveals that NMC811 chemistry tends to be more expensive than LFP in terms of cost per kWh. This is primarily due to higher costs of critical components in the Cathode Active Material (CAM), particularly nickel and cobalt. This factor has contributed to the growing market share of LFP in ESS applications. However, it should be noted that LFP manufacturing is relatively more expensive than NMC811 due to the greater cost associated with current collector foils (copper and aluminium) and polymeric separators. In the baseline (2023) scenario, manufacturing costs are 16% and 22% of total cell cost for NMC811 and LFP respectively, rising to 20% and 27% respectively in 2030.

In China, the price for prismatic LFP cells was US$94/kWh in May 2023; 2% higher than prismatic NMC811 cells, representing a reversal since November 2022 when LFP was 19% cheaper than NMC811 cells in China[21]. The main driver for this increase was the rise in lithium carbonate prices, which represents the highest cost in LFP cathode active material. Concurrently, prices for nickel and cobalt sulphate fell around 4% and 13% respectively in Q1 2022, both of which are principal active materials in NMC811. Price volatility of battery-grade active materials is expected to

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[19] Kebede et al, 2022. A comprehensive review of stationary energy storage devices.

[20] Benchmark Mineral Intelligence 2022.

[21] Source: Benchmark Mineral Intelligence on 21-June 2023

continue in the short-term as the market continues to be sentiment-driven, resulting in further price fluctuations over the coming period. The market, however, is expected to be more predictable longer-term i.e., beyond 2025. Any price fluctuations are expected to be closely tied to the cost of lithium carbonate rather than the actual cell cost, with prices determined on a cost-plus margin basis.

The chief concern for LFP pricing is that virtually all manufacturing capacity is concentrated within China, thus presenting supply bottlenecks to the rest of the world. Significant capital investment in the order of US$11-20B will be required to meet the future demand for LFP in BESS outside of China. Around 151GWh of LFP will be required for BESS by 2030, of which 105GWh will be needed for grid applications.[22]

Silicon anode pathway to cost optimisation and implications

At its Battery Day in 2020, Tesla stimulated interest in silicon anode by suggesting it could optimise its variable costs for silicon anode technology to US$1.20/kWh[23] using silicon nanowires versus incumbent graphite anode, which is anywhere between US$8-12/kWh. The company claimed that current engineered approaches to silicon are expensive and wasteful, but can be improved through the removal of purification, mechanical, and slurry mixing steps; a claim that is also supported by OneD Battery Sciences[24], while other companies, such as Sila Nanotechnologies, claim that it will optimise lithium-ion cell prices to around US$50/kWh by 2030 using silicon structured in graphite either metal fluoride or sulphur-based cathodes.[25]

Silicon anode should theoretically be cheaper to manufacture at scale (in US$/kWh) because less material is used than traditional graphite. Further cost reductions and greater energy efficiency in the cell can be achieved through the use of fewer and faster processing steps, facilitated by the use of a copper catalyst to decompose silane gas into nano-silicon. The costs of capital equipment, such as those used for chemical vapour deposition (CVD), can also be amortised contributing to an overall cost reduction. However, this has yet to be proven at scale, while swelling issues associated with silicon during cycling also provide a performance barrier, which causes significant cracking and pulverisation of the cell at greater than 300 cycles.

The cost pathway for lithium-ion cells was modelled which included various evolutions of silicon anode to 2030. These results were compared to a present day baseline graphite anode (either natural or synthetic) blended with 5% silicon additive versus non-optimised and optimised (e.g., micro-silicon with pre-lithiation) versions of silicon-dominant active anode material. For consistency, all examples are paired with an NMC811 cathode and liquid electrolyte.

The results show that current anode active material typically accounts for 7% and 9% of total cell cost in NMC811 and LFP respectively. This is expected to reduce to 2% of total cost in both NMC811 and LFP by 2030, allowing for an optimised version of micro-silicon at scale, as depicted in Figure 36. It is assumed that many of the

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[22] Rho Motion, BESS Outlook Q1 2023.
[23] Tesla Battery Day, September 2020., Benchmark Mineral Intelligence, 25-September 2020.
[24] OneD Battery Sciences.
[25] Lei et al, 2017.

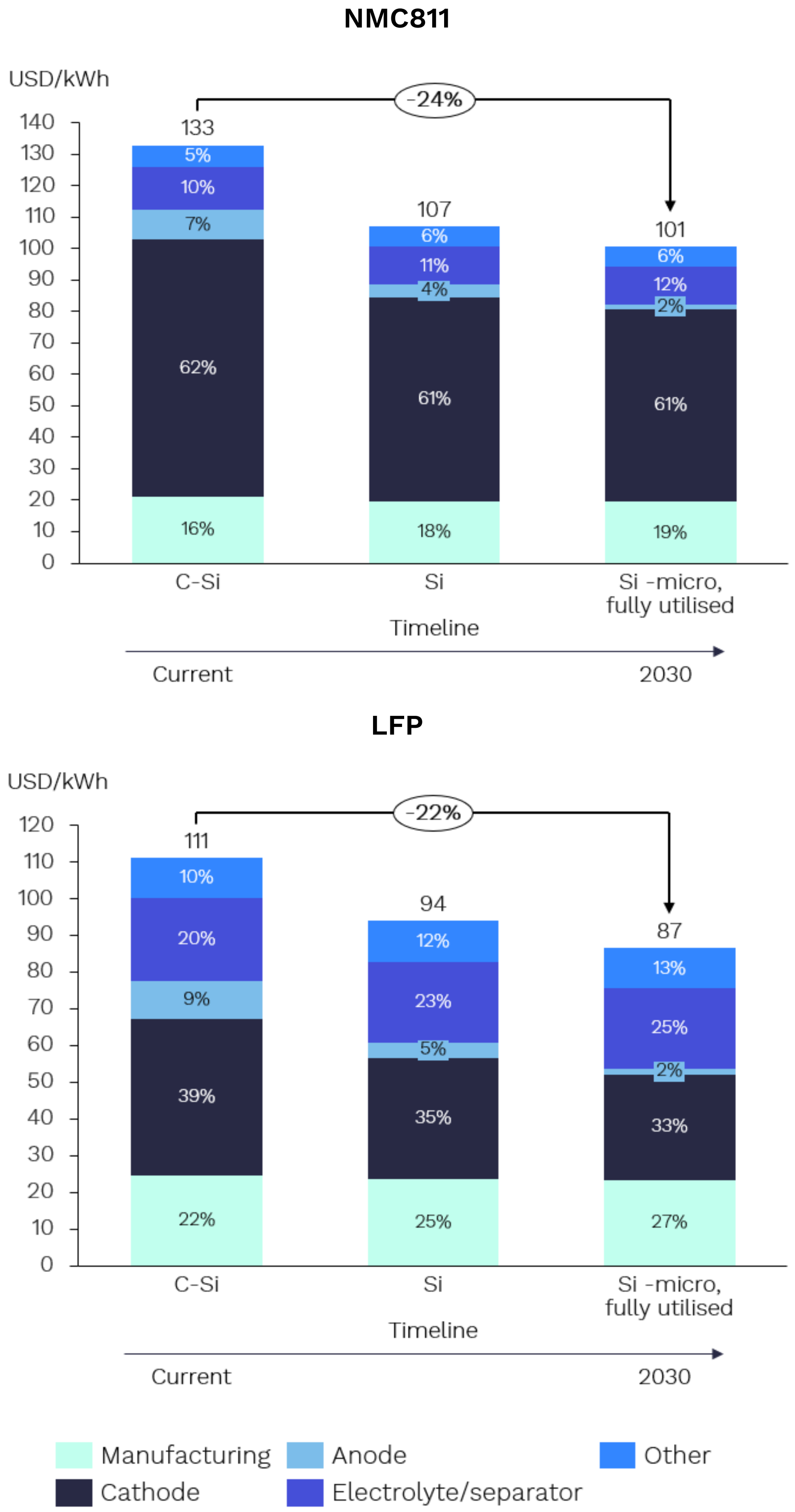
technical challenges associated with silicon anode will be resolved by 2030, and improved cell efficiency will be driven by higher energy density, potentially achieving around 240Wh/kg. However, this advancement will require optimisation through improved processing methods.

Through manufacturing-led innovations and supply chain synergies, active anode material could be reduced from around $12/kWh to a potential cost floor of around US$2-4/kWh. Cost reductions can be achieved through the conversion of metallurgical-grade silicon into nano-Si particles because of less reliance on the production of carbon or polymer matrix, which will result in lower energy intensity, waste and smaller carbon footprint due to faster and simpler processing. Through the adoption of pre-lithiation, silicon composites can maintain first-cycle efficiency which, in turn, avoids additional cathode costs associated with plating and pulverisation that will result in shorter cycle life.

Dry electrode processing has the potential to increase first-cycle efficiency through the addition of a lithium powder pre-lithiation, but is in a very early development stage with no clear pathway to scale-up. However, it could result in fewer processing steps compared to traditional wet coating which uses N-Methyl Pyrrolidone solvent (NMP) and avoids impurities introduced when the solvent reacts with the electrolyte.

Other anode technologies containing LTO and Niobium-based active material were not explicitly modelled but implied through modelled cell scenarios with lower energy density and higher N/P ratio. Further work would be required to perform bottom-up models for LTO and Niobium-based anodes based primarily on industry analogues from companies such as Echion, Nyobolt and Toshiba.

Figure 36. Pathway to anode cost optimisation, current to 2030



Source Rho Motion

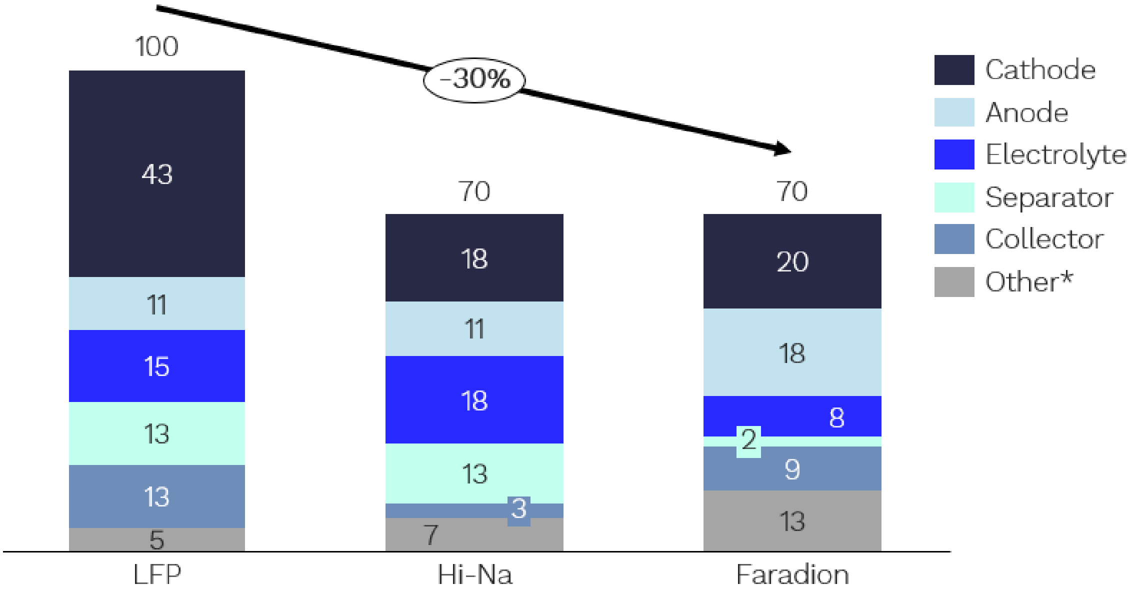
Sodium-ion cost and implications

Sodium-ion technology has emerged as a potential cost-competitive alternative to LFP. Initial cost modelling suggests that sodium-ion batteries could have up to 30% lower material costs compared to LFP, as shown in Figure 37[26].

Several companies are developing various sodium-ion technologies: CATL, HiNa Technology, Natron Energy, and Faradion. CATL's announcement in August 2021 regarding the commercialisation of its Gen-1 batteries for BESS applications was seen as a significant breakthrough in the industry. However, updates on progress and confirmation of mass production have remained limited since then. HiNa recently achieved a scale of approximately 1GWh of sodium-ion cell production in China.

Sodium-ion supply chains are expected to be more manageable than traditional lithium-ion batteries due to the utilisation of fewer raw materials and less complex processing methods.[27] Moreover, existing production lines for lithium-ion battery production lines can be readily converted to produce sodium-ion batteries, offering cost savings through amortised equipment costs that would otherwise be incurred with the development of entirely new product lines. In recent years, as renewable energy has been commercialised at a much larger scale, so has the demand for sodium-ion in BESS.

Figure 37. Top-down cell cost - LFP versus sodium-ion



Source HiNa Tech, Faradion and Advanced Propulsion Centre (APC) analysis, 2021.

**Other includes foils (both anode and cathode), conductor additives, solvents and binders.*

The sodium-ion cell cost scenarios were modeled and compared to a 2023 baseline cell, produced at a pilot-scale by an undisclosed developer, across various future scenarios of optimised energy and power cells. It was assumed that the performance and cost metrics for future scenarios would be based on the scaled

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[26] Source: Hi-Na Tech; Faradion; Advanced Propulsion Centre (APC) analysis, 2021

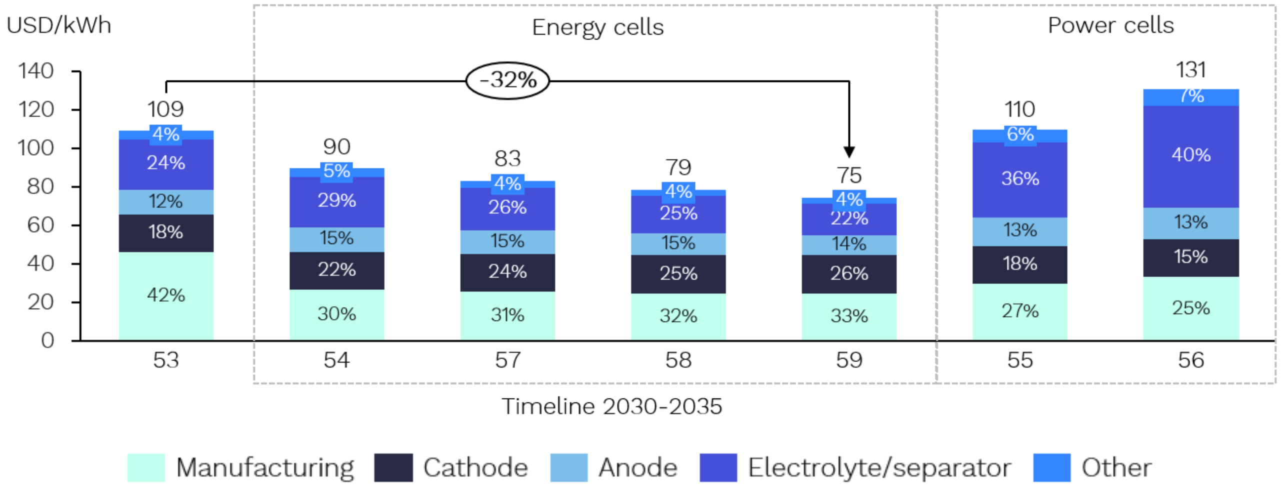
[27] Yadav et al (2022) Sodium-based batteries: development, commercialisation journey and new emerging chemistries.

plant with a capacity of 10GWh/yr and based in the UK. All cells in each of the cost scenarios are assumed to use a liquid electrolyte and a hard carbon anode.

The results show a clear pathway to cost optimisation. In the 2025-2030 period, Sodium-ion cells are assumed to achieve marginal cost efficiencies through the active materials in the cathode, such as nickel reduction, anode, and electrolyte, and through optimised manufacturing at scale, as illustrated in Figure 38. In the post-2030 period, further cost reduction is assumed to come through cheaper anode and electrolytes; both at 20% less than today's baseline example, translating to a 32% cost reduction across the entire cell.

In addition, sodium-ion 'power' cells were modelled, analogous to Natron's in terms of reported energy density, at around 150Wh/kg. Those power cells revealed a higher total cell cost versus today's baseline model, but with a higher N/P ratio than modelled 'energy' cells. In the most optimised example, the total cell cost was roughly the same as the baseline model; US$110/kWh versus US$109/kWh for future optimised power cells and today's pilot-scale sodium-ion respectively. The results indicate that sodium-ion power cells could provide a viable cost and performance alternative to other power cells, especially when companies such as Natron are reporting a charge time of eight minutes, a minimum service life of five years and 35,000 cycles without capacity loss.

Figure 38. Sodium-ion pathway to cost optimisation



Note – the numbers 53 to 59 represent the modelled scenario number

Source Rho Motion Cell Cost Model

Sodium-ion versus LFP cost and implications

The results (

Figure 39) reveal that sodium-ion is cheaper than LFP, even in a high-cost scenario. The cost difference between LFP and sodium-ion is principally driven by the bill of materials; active material costs are greater in LFP than sodium-ion. In addition, aluminium foil can be used in both anode and cathode, which avoids the use of expensive copper and alloying with sodium-ions on the anode side, thus translating to further cost savings relative to lithium-ion cells.

Manufacturing costs, however, are more expensive in sodium-ion, both as a proportion of total cell cost and in absolute terms, because of greater energy intensity, resulting in the need for more electricity to power operations.

The sodium-ion model assumes a mature cell, a concept that is unproven and is not currently available in the market. For example, although above 200 Wh/kg cells are currently being tested by start-ups developing advanced layered oxide cathodes, these remain unproven at scale. CATL is currently proposing 160Wh/kg for sodium-ion and a higher energy density of around 180Wh/kg for LFP, which is close to the theoretical limit of 200Wh/kg.

Sodium-ion, therefore, provides a cheaper cost alternative and the potential to de-risk the value chain and ESG footprint without compromising its performance.[28] Furthermore, sodium-ion has an added advantage over LFP because it does not suffer from performance issues at cold temperatures (it can operate between -20 and 60°C).

CATL expects to achieve a total cell cost of US$30-45/kWh at scale for its Prussian Blue cathodes, owing to lower costs associated with iron-based cathode and synthesis. The true cost competitiveness of sodium-ion compared to LFP, however, is expected to be minimal until economies of scale are realised, and supply chains are solidified.

Sodium-ion is anticipated to be a credible technology for BESS grid applications, owing to its safety and performance under extreme operating conditions, but it must receive significant investment and overcome scale challenges before it can be considered a viable alternative to LFP.

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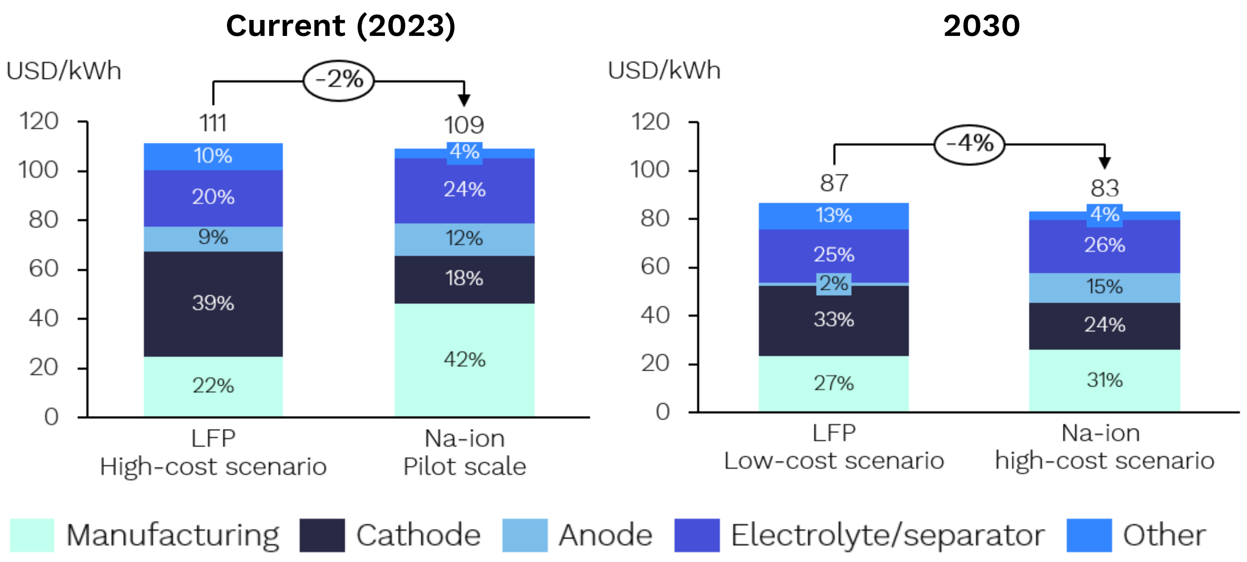
[28] Engineering of Sodium-Ion Batteries: Opportunities and Challenges - ScienceDirect

Figure 39. Sodium-ion vs LFP modelled cost and performance comparison



Source Rho Motion Cell Cost Model

**Na-ion assumed to be paired with liquid electrolyte, hard carbon anode*

	LFP	Sodium-ion
Energy density	180Wh/kg*	160Wh/kg**
Voltage	3.2V	3.2V
Discharge rate (at -20°C)	<70%	>90%
Fast charging	N/A	80% in 15 mins
Safety	High	High

**CATL assumed before cell-to-pack optimisation using Qilin 2.0*
***CATL assumed state-of-the-art, yet unproven at scale*

Next generation solid-state electrolyte cost and implications

Solid-state electrolytes typically have high mechanical strength and high ionic conductivity, allowing for the parallel pursuit of energy density and safety in all solid-state designs. The solid electrolyte is compatible with silicon or lithium metal anode material, and not mutually exclusive, making these important future technologies for lithium-ion battery cells.

While lithium metal represents the maximum possible energy density for anode material, anode-free or ''anode-less'' battery designs are also emerging due to their high (theoretical) energy density and lower cost. However, anode-free designs are susceptible to substantial metal dendrite growth and SEI instability, while remaining unproven for long cycling or high Coulombic efficiency. Typically, NMC chemistries are used to maximise energy density but, in principle, various cathodes can be paired with solid-state electrolytes.

Oxide and sulphide (both inorganic), and polymer forms of solid-state electrolytes were modelled and paired with either NMC811 or LFP cathode, and various anodes. A baseline (2023) scenario was established using a cell containing liquid electrolyte and C-Si anode (with 5% silicon additive) versus next-generation electrolyte and anode evolutions, indicative of various expected scenarios between 2030 and 2035. In all future scenarios, active material (e.g., Li, Ni, Co, Mn, C) prices remain fixed, and linked to forecasted long-term incentive prices to see the relative cost impact when optimising the performance characteristics of the cell.

The results show a clear pathway to cost reduction for all solid-state forms, both for NMC811 and LFP cathodes, as shown in Figure 40 and Figure 41 respectively. Oxides generally start from a higher cost base relative to today's state-of-the-art cell technology, and sulphide and polymer solid-state electrolytes, because of the catholyte gel, which is dense enough to be parasitic to the overall specific energy of the cell, thus increasing the cost per kWh. This results in electrolyte and separator having the highest cost contribution to the cell; in many scenarios around 50% of total cell costs.

Cost improvements are plausible through the introduction of a silicon anode, assuming the adoption of a fully utilised, micro-silicon with pre-lithiation, and lithium-metal using chemical vapour deposition methods. However, cost reduction is only noticeable for NMC811; 22% in the most optimised anode-less case, while for LFP, there is no clear route to a cheaper cell cost than today's state-of-the-art. There are, however, no cost scenarios for both NMC811 and LFP that show a clear pathway to sub-US$100/kWh when using solid-state oxides, at present.

Sulphides and polymers currently have a more plausible pathway to greater cost reduction, potentially bringing them close to cost parity with sodium-ion. Concurrently, modelled sulphides and polymers with optimised anode offer double the energy density of sodium-ion, significantly faster charging time, equivalent to around 10-20 minutes, and greater safety than present day lithium-ion deployed in EV and BESS. Energy density improvements are likely to be more pertinent for NMC811 where it is already being deployed in EV applications, and where range is a key requirement. This may be less significant for BESS although grid-scale applications could still benefit from a piggyback effect that the EV sector will bring, as greater performance and lower cost cells become more pervasive and more readily available over the next decade.

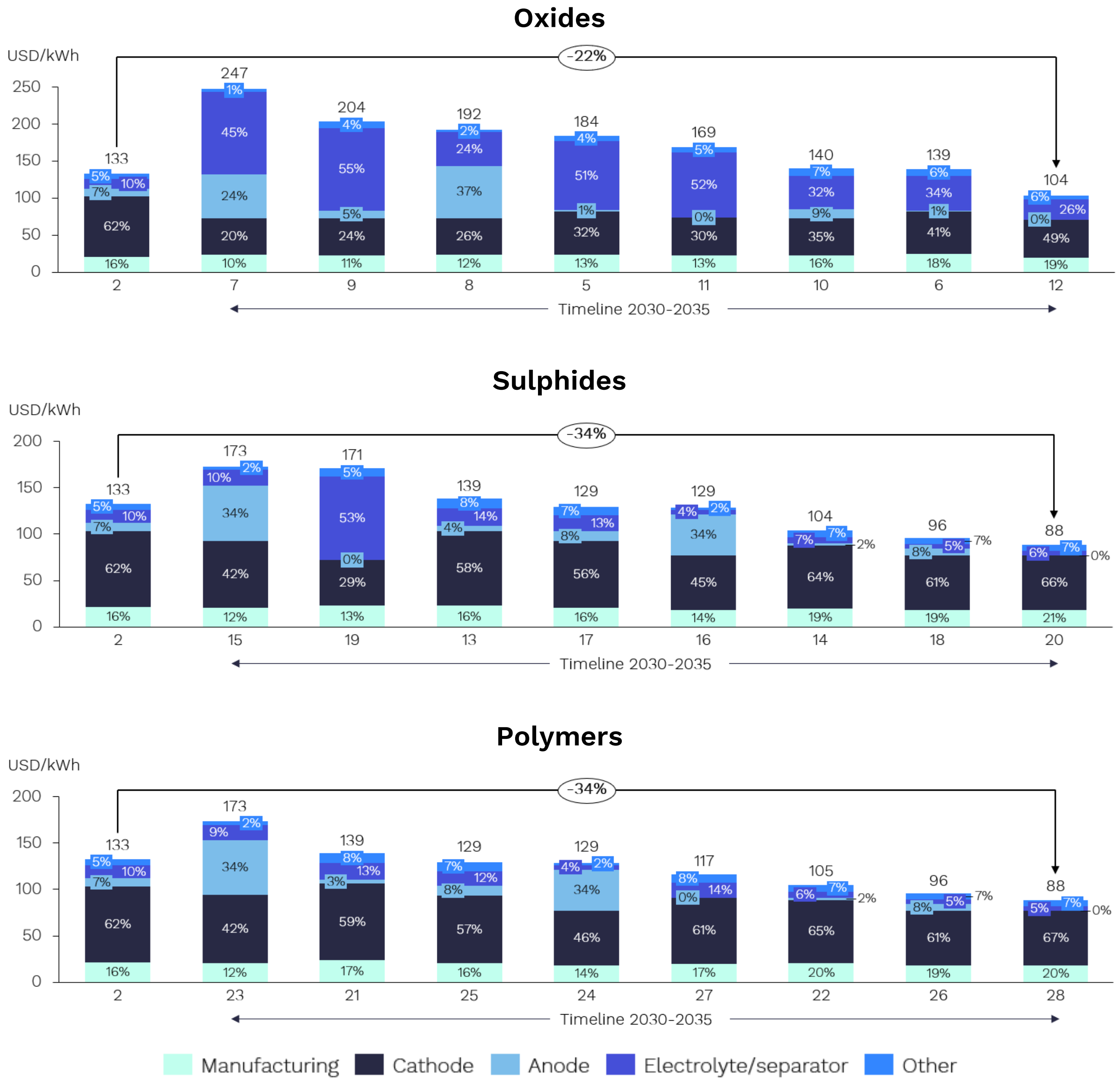
All modelled scenarios for ''optimised'' NMC811 and LFP paired with any form of solid-state electrolyte required a thinner separator, around 20 microns, and cheaper electrolyte material, at an assumed 20% cost reduction relative to today's prices. Here, only sulphides and polymers achieved costs below US$100/kWh assuming both would likely need to overcome challenges associated with lithium plating and dendrite formation to preserve cycle life.

The results also suggest that significant optimisation of lithium metal anodes would be required to bring them close to cost parity with fully optimised silicon-dominant anodes, thus making them a less viable option at present. It is expected that there is a clearer cost reduction pathway through CVD than rolled lithium metal, at present, and therefore will likely be realised at a commercial scale sooner.

The cost of lithium metal is a key function of thickness. Lithium metal is cheapest at greater thicknesses i.e., above 40 microns (and extruded during rolling), but has lower productivity relative to thinner material. Thick lithium metal becomes prohibitively expensive to roll, owing to the complex process associated with rolling thin sheets of lithium, and contributing to around 30% of total cell cost when assuming a conservative solid separator thickness of 40 microns and catholyte solid content of cathode at 30%wt. However, it is also difficult to roll thinner lithium material, which requires treatment to coat, thus resulting in a higher cost.

The results suggest that lithium metal can achieve cost savings primarily through the use of a thinner separator i.e., around 20 microns, catholyte content of 10-15%wt, and reduction of copper foil at the negative electrode as much as possible while still effectively functioning as a current collector. This results in an energy density increase of 60% versus a non-optimised scenario, translating to an approximate cost reduction of US$40/kWh. Nevertheless, the cost is still substantially higher than fully optimised micro-silicon and further work will be needed to understand where further cost reductions can occur.

Figure 40. Cost model scenario results for NMC811 with solid-state electrolytes*



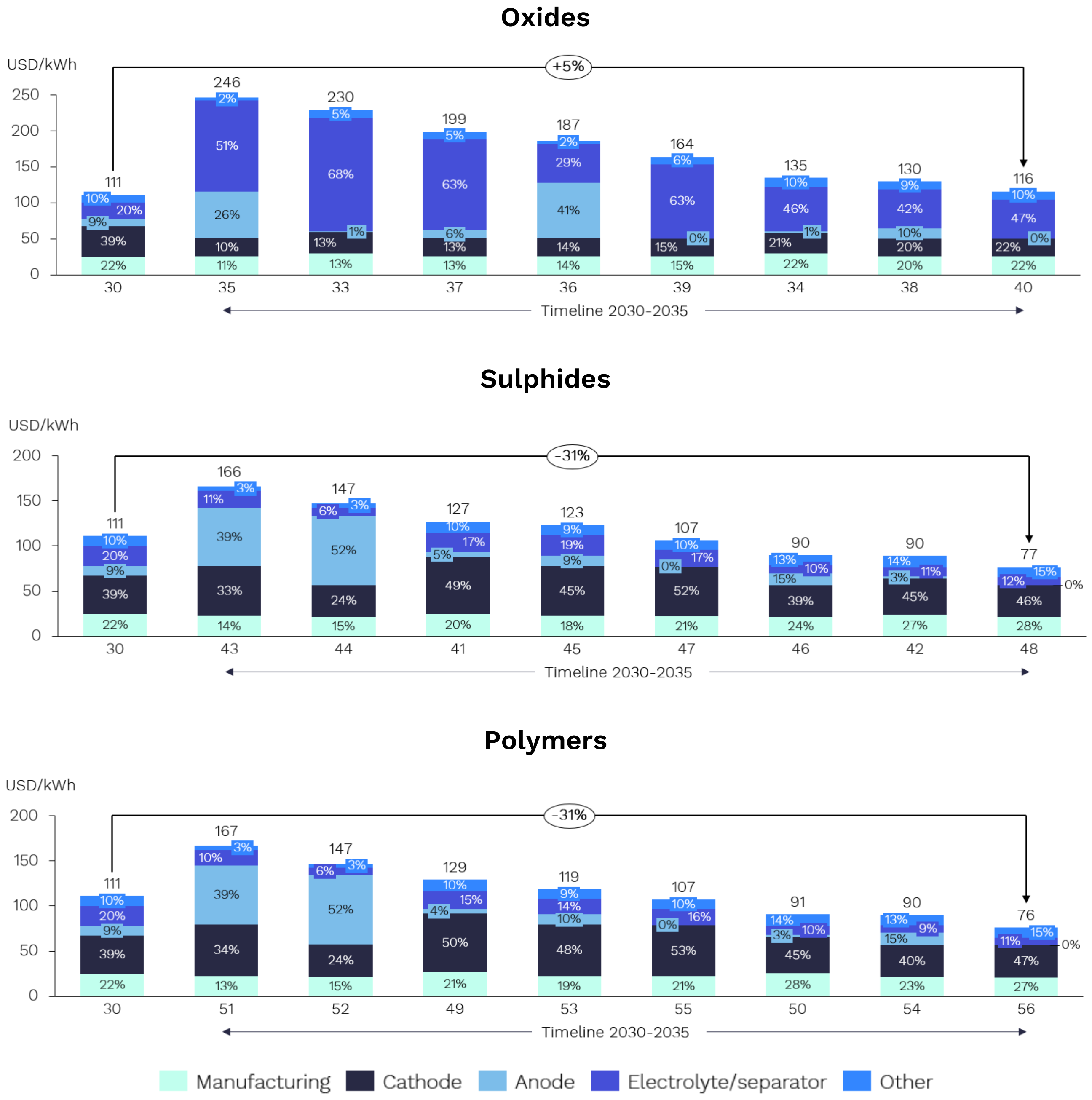
Note – the numbers 2 to 28 represent the modelled scenario number

Source Rho Motion Cost Model

Key assumptions

- *Model 2 baseline (2023) NMC811 cell paired with liquid electrolyte and C-Si anode (5% Si additive).*
- *Model 5-28 NMC811 paired with different solid-state electrolytes, and assumed with increasing level of optimisation from 2030 to 2035. Note that some modelled scenarios are based on cells that are currently under development in industry and therefore analogous to today's state-of-the-art at the lab-scale, while others have no clear route to scale, at present. For a detailed breakdown of cell cost scenarios see Annex I*

Figure 41. Cost model scenario results for LFP with solid-state electrolytes*


Oxides

Sulphides

Polymers

Source Rho Motion Cost Model

*<u>*Key assumptions</u>*

- *Model 30 baseline (2023) LFP cell paired with liquid electrolyte and C-Si anode (5% Si additive).*
- *Model 33-56 LFP paired with different Solid-state electrolytes assumed with increasing level of optimisation from 2030 to 2035. Note that some modelled scenarios are based on cells that are currently under development in industry and therefore analogous to today's state-of-the-art at lab-scale, while others have no clear route to scale, at present. For a detailed breakdown of cell cost scenarios see [Annex I](#)*

7. Opportunities and challenges for further UK research, policy and legislation

This section examines the opportunities and challenges for further UK research in BESS, focused on battery technologies, battery management systems, battery recycling and the development of manufacturing capabilities. It also addresses the need for supportive legislation and regulation, as well as reforms in the electricity market to incentivise low-carbon investment.

Challenges to progress BESS in the UK

BESS and EV manufacturing

Currently, the UK is in the early stages of developing commercial-scale battery manufacturing capabilities. If the UK does not manage to develop these capabilities in a timely fashion, future demand for BESS equipment (particularly battery packs) will need to be met by global manufacturers instead of local production, limiting the benefits for the UK manufacturing industry and the wider economy. Additional costs may also occur as BESS developers and investors will need to develop business models that are resilient against supply chain constraints and volatility.

The only battery cell operating at a commercial scale in the country is AESC UK, which produces NMC cells for EVs manufactured by Nissan. However, Tata Group has recently announced a £4 billion investment to build a UK gigafactory in southwest England. Expected to be operational by 2026, this plant will be one of the largest in Europe and produce nearly half of the UK's battery capacity needed by 2030.

Global battery manufacturers and OEMs have until now been deterred by a combination of weak political backing and financial ambiguity. For example, EV manufacturing giants BYD and Stellantis, have voiced concerns in the past over the UK’s ability to remain competitive in the global EV and battery value chain. Some of the company’s fears were predicated on a lack of financial incentives such as production tax credits and subsidies, and associated policy instability following Brexit. Meanwhile, Volkswagen recently selected Canada for its first EV plant outside the EU, having been lured by US production incentives under the Inflation Reduction Act. While the Envision and Tata plants are welcome developments, if the UK government does not continue to intervene, it faces the possibility of losing foreign direct investment in the future, as battery manufacturers aim to diversify their supply chains.

Regulatory

The UK currently has no set energy storage target and largely relies on renewable deployment to have an organic effect on large-scale BESS deployment. The UK has made minor legislative progress, including the removal of double taxation for electrical charges and discharge from energy storage assets, but there are still regulatory barriers to be overcome, including:

- Projects still face significant planning permission lead times and grid connection delays.

- Revenue stacking is a complex and opaque area for investors and asset operators, which has discouraged private sector investment and new market entrants.
- Network providers can only invest in building capacity based on the connection requests they have received, meaning a queue of projects is required before network capacity can be expanded, which itself is a lengthy process.
- Regulation incentivises network operators to minimise costs, rather than achieve Net Zero.

To unlock BESS deployment blockers, the UK government is currently drafting an Energy Security Bill, pending House of Commons deliberation. The legislation intends to repeal the 1989 Electricity Act and redefine energy storage as a distinct subset of energy generation. This will provide certainty over how energy storage is treated during the planning and licensing of projects and possible future frameworks. It also intends to facilitate the deployment of electricity storage by providing legal clarity over the defined role of energy storage, leading to more precise market reform and greater investor certainty on energy storage projects, while still allowing flexibility for treating storage differently to other forms of generation where appropriate. International developments in energy storage legislation are summarised in *Annex I.*

Electricity market reform

The UK government recently published its first consultation on the Review of Electricity Market Arrangements (REMA) in 2022, setting out the case for change and an initial assessment of its options. The most relevant policy proposal is to incentivise low-carbon investment by retaining and reforming the Contracts for Difference (CfD) scheme to reduce dispatch distortions. Changes to the capacity market will also be required to address the grid flexibility challenges and to phase-out non-low-carbon solutions, not only restricted to peak capacity applications.

There is an additional challenge to improve dispatch efficiency through stronger locational signals in the wholesale market and more accurate market signals for curtailment that can help address the energy mismatch. Wholesale market changes must also consider potential changes in governance arrangements for the distribution system and the emergence of markets at the distribution level. Effective customer engagement can also unlock flexibility from small-scale assets and improve affordability through efficient signals, competition, and transparency.

As the proportion of UK renewable energy sources increases and efforts to achieve Net Zero emissions involve the electrification of transport and heating sectors, it is crucial to have a more comprehensive techno-economic understanding of BESS applications.

Opportunities for UK research

This study evaluated the current and next-generation electrochemical storage technologies that would be primarily suited to different stationary storage applications for the grid in the UK, considering technologies that are likely to be commercially deployed in the period to 2035. Whilst batteries currently offer an array of short-duration storage optionality, there are research opportunities in exploring their use in medium-to-long-term, i.e., hourly to monthly, duration applications.

The detailed evaluation included technical and technological considerations related to each battery cell technology, including the direct opportunity and applicability to the UK ESS market. Several factors were assessed for technical and commercial relevance, cross-application applicability, scalability, supply chain, ESG credentials and cost.

Each of the assessed electrochemical storage technologies were analysed in terms of the relative opportunity and UK compatibility to delineate their prospects and recommendations for further research. This included a broad overview of the following electrochemical forms and their respective subsets:

- Lithium-ion: NMC 811, LFP; Si, Li-metal, LTO anodes; solid-state electrolytes
- Sodium-ion: energy and power cells
- Redox flow: vanadium, zinc-bromine, zinc-iron
- Metal-air

The research opportunities were classified into four categories to reflect the extent of prioritisation that each electrochemical form could expect in the context of the future UK grid needs, as illustrated in Figure 42:

- **Mainstream conventional:** either commercially deployed or viable
- **Alternate solutions:** at a technology readiness level (TRL) of around 4-5[29]
- **High value / low opportunity**: requires a left-of-field innovation to unlock the true value of the opportunity
- **Rank outsiders**: still at the conceptual/small prototype stage (TRL 1-4)

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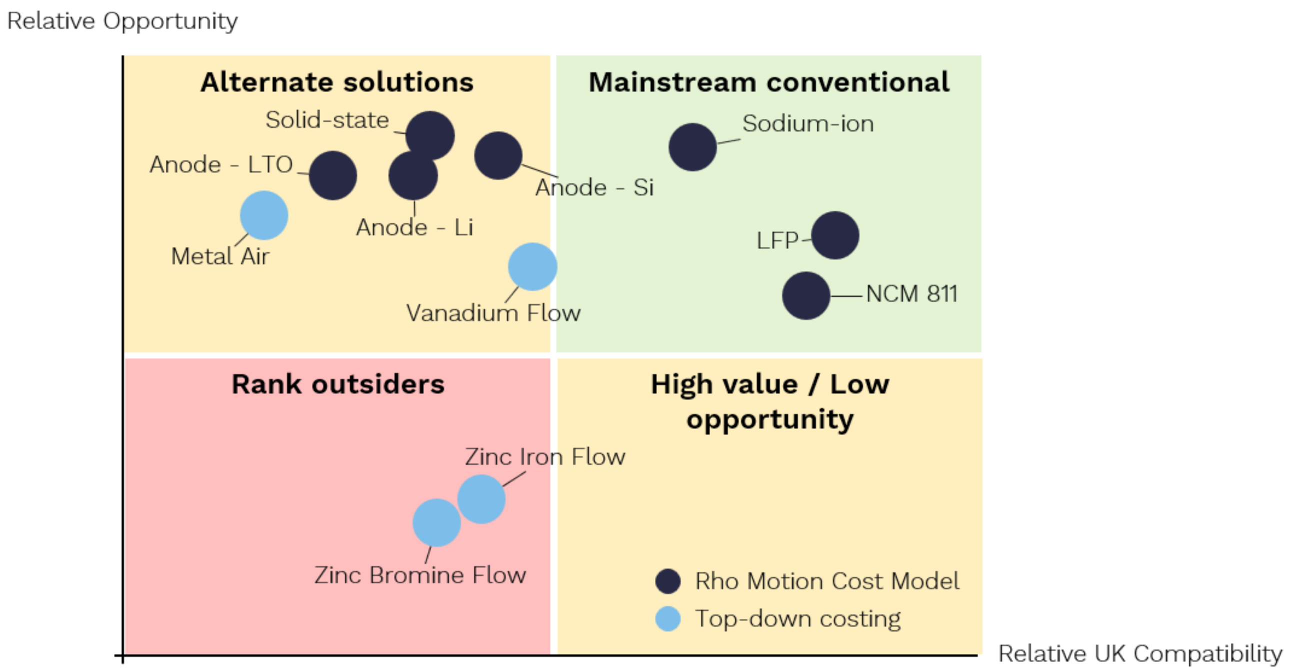
[29] Frith, J.T., Lacey, M, Ulissi, U., 2023, A non-academic perspective on the future of lithium-based batteries

Figure 42. Battery technology UK opportunity versus grid compatibility



Source Rho Motion

In the short-term, BESS with durations of seconds-to-hours is closely aligned with the growth of the EV market. Two clear areas of technology likely to increase in importance for increased BESS adoption and thus further research are **LFP** and **Sodium-ion batteries.**

Lithium-ion batteries are widely recognised for their excellent performance across response time, discharge duration, and round-trip efficiency. They offer fast response times, versatility in discharge durations, and high round-trip efficiency, meaning they lose less energy per cycle than other technologies, making them a preferred choice for various grid flexibility applications.

LFP batteries are reaching their theoretical limit at the cell level and therefore next-generation innovations are needed to optimise cell performance.

The leading LFP producers, which are all based in China (e.g., CATL, BYD, CALB, Gotion High-Tech and EVE) and primarily selling their LFP cells in the EV sector, are customising cell format to improve cell performance and expand to BESS applications. Some developers, such as CATL and SAFT, are exploring doping with other metals to increase energy density and testing new chemistries like LxFP, which involves the partial substitution of dopants such as 'Mn', 'Al', and 'V', while Gotion High-Tech recently announced its intention to mass produce its lithium manganese iron phosphate (LMFP) product in 2024. LMFP is characterised by trade-offs for BESS applications. It offers a higher voltage and energy density at the same capacity as current LFP, but with limited power capability and cycle life, making it less relevant, but potentially more cost efficient, in BESS applications. Optimised LFP cell costs will likely be incremental, achieved through design and manufacturing improvements or a reduction in the cost of active materials.

UK research efforts for LFP in BESS grid applications can benefit from the ‘piggyback’ effect that is currently occurring in the EV sector. Battery management systems, while researched in EVs, are receiving less attention in BESS.

Silicon anodes are widely expected to be the next major cell innovation for lithium-ion that will significantly improve theoretical capacity and fast charging (C-rate) capability. The theoretical capacity of silicon is ten times that of graphite, which is currently deployed as the main anode active material.

High capital investment in anode research and development projects demonstrates the wide acceptance that the next major cell innovations will be made in this field. While energy density is less important to BESS applications, the C-rate potential for silicon is likely to improve cost per kW.

In the development towards pure silicon anodes, some OEMs are already blending around 5% silicon additive with graphite to form C-SiOx active anode material. This has allowed some OEMs, for example Gotion Hitech to achieve higher energy density at the cell level, where they are aiming to reach up to 260Wh/kg.

When using pure silicon anodes in the cell, metallurgical-grade silicon is needed. This requires additional processing to purify, and then to micronise into a powder. Silicon may then need to be coated with amorphous carbon or a conductive polymer to mitigate the effect of expansion and then intercalated with a carbon matrix.

Research opportunities could seek to reduce the cost of silicon anode precursors through vertically integrated scaled (and mature) supply chains driven by four primary materials:

- Graphite (mature, standard supply chain)
- Silane gas (mature, standard supply chain from solar cells)
- Nitrogen (extracted from ambient air, inexpensive)
- Copper (negligible amount, inexpensive)

Additional research opportunities could explore the following:

- Chemical Vapour Deposition (CVD), a reactive process that creates silicon nanoparticles for improved uniformity and energy density in the anode active material.
- Pre-lithiation of pure silicon anodes. Without pre-lithiation, any cell would likely achieve around 80-85% first-cycle efficiency. Pre-lithiation of pure silicon anodes can be applied to achieve higher first-cycle efficiencies (around 90%), which in turn leads to higher energy densities at the cell level. The cost of pre-lithiation is likely to be a function of lithium thickness (in microns) or the desired pre-lithiation capacity, typically 5 microns of lithium or 1mAh/cm^2.

Lithium metal is commonly regarded as the holy grail in the battery industry in terms of anode performance, with a theoretical capacity ten times greater than present day graphite. However, it faces significant technical challenges to be widely available in the market. It is generally assumed that lithium metal would need to be paired with solid-state electrolytes to maximise cell performance and there are notable performance trade-offs with cost.

One of the key questions to answer when using a lithium metal anode is whether to use a thin piece of lithium on a current collector, or to use a thicker piece of lithium which is easier to process. Using a current collector and a thinner lithium coating incurs an energy density penalty, as copper has an energy density almost 20 times higher than lithium. However, costs are significantly lower as you do not need to use a huge excess of lithium at the anode. The opposite is true when using no current collector: energy density is increased significantly more, however there are large costs due to the excess lithium used to achieve a thicker, more processable anode. There are a handful of companies producing "current collector" free batteries with thick lithium foils, e.g., Blue Solutions and formerly Solid Power.

Other important areas of research include using CVD to coat thin layers of lithium onto substrates, or the use of anodeless cells. Cost is also an issue which must be addressed to enable the commercialisation of this technology.

UK research efforts could explore anodes that reduce the volume of material needed to achieve faster charging and reduced cost per unit because of greater volumetric density; this is vital for short duration flexibility applications. Therefore, lithium metal using CVD methods with varying volumes of copper substrate and alternative current collector materials is likely to be a good starting point, especially considering that upfront costs could be offset for CVD equipment that is already used to construct solar cells.

Solid-state electrolytes are widely seen as a long-term solution to better electrochemical stability at the cell-level, offering longer cycle life and greater battery safety.

At present, pursuing oxide-based solid-state electrolytes is questionable for the UK because of the greater cost associated with catholyte gels that are currently used, despite companies such as Ilika developing the technology. Oxides could be cheaper provided they can be made very thin at scale to overcome their hugely parasitic nature regarding specific energy. The current roadmap to achieving cost parity with sulphides and polymers is difficult to envisage but could be achieved with more research into the use of thinner oxides and different catholyte gels.

While sulphide and polymer-based solid-state electrolytes appear to be clear winners in terms of current and future cost efficiency, the route to market for all solid-state forms is likely to be long and at least ten years from now. Polymer and sulphides may eventually achieve cost parity with sodium-ion but would likely require mature supply chain development and cheaper salts for the active material.

All forms of solid-state technology are likely to require pairing with either fully-optimised silicon or lithium-metal anode in order to achieve higher energy densities. At present, silicon provides a clearer pathway than lithium metal to a scalable anode solution. There is, however, the potential for lithium metal to transform battery design.

UK research efforts could explore the development of silicon anodes paired with polymers or sulphide solid-state electrolytes, while lithium metal and solid-state oxides could be part of a longer-term research strategy aimed at maximising performance and minimising cost in BESS grid applications. Research into the use of thinner separators could also provide a potential route to significant cost savings at the cell level.

Sodium-ion batteries have only recently entered the commercial market in small volumes in China and so are still very much under development. Sodium-ion batteries exhibit technical characteristics like their lithium-ion counterparts, in terms of response time, discharge duration, and round-trip efficiency. They can provide fast response times, support extended discharge durations, and have the potential to achieve high efficiency levels. Sodium-ion batteries offer cost competitiveness and performance parity and are manufactured from abundant and widely available active feedstock material compared to their lithium-ion counterparts.

The key research challenge is to improve the performance and durability of sodium-ion batteries. Research projects could explore:

- Developing new cathode and anode materials that improve battery energy density, cycling stability, and overall performance.
- Optimising the electrolyte composition and design to enhance the battery's efficiency and reduce degradation over time.
- Identifying the potential risks and hazards associated with sodium-ion battery operation and developing strategies for their safe handling and disposal.
- Exploring ways to minimise the environmental impact of sodium-ion batteries, such as using earth abundant elements in the cathode.

Redox flow batteries excel in applications requiring longer discharge durations, reduced response time and competitive round-trip efficiency characteristics compared to non-electrochemical energy storage technologies. Redox flow batteries offer some advantages over traditional lithium-ion batteries, such as scalability, longer cycle life, and flexible discharge durations trending to longer duration, which means they can support both short-term and long-term ESS needs. Flow batteries are likely to be particularly useful for meeting the demand for longer duration storage.

Flow batteries, similar to metal-air batteries, are too large to be deployed in EV applications. As such, neither have benefitted from the significant investment in research and development that lithium-ion and sodium-ion batteries are receiving. The Faraday Institution has funded a few small-scale projects around the development of new electrode materials and battery designs for zinc-flow batteries as well as lead/lead oxide flow batteries. There are also other UK based research institutions which are actively working on flow batteries. However, there are still several challenges that need to be addressed to fully realise their potential, which could be explored in further research. Flow batteries, similar to metal-air batteries, are too large to be deployed in EV applications. As such, neither have benefitted from the significant investment in research and development that lithium-ion and sodium-ion batteries are receiving.

The favoured chemistry for flow batteries is currently vanadium, primarily due to its ability to stay in solution through a range of oxidation states, allowing for a greater degree of energy storage. However, vanadium of suitable quality for flow batteries is expensive and, additionally, in some forms can be toxic. Developing a new electrolyte, that uses different transition metals as the active ingredient, may reduce cost. There are multiple avenues that electrolyte development can take, such as organic, carbon-based electrolyte solutions. One notable commercial example of novel flow battery technologies can be seen by US based firm, ESS Inc,[30] who have pioneered an iron flow battery that has reduced the cost curve of energy storage. The company claims that iron-flow batteries provide a more harmonious mix of energy storage, cost and ESG credentials than those of flow batteries for vanadium and zinc but beyond ESS Inc, there is a limited commercial application for alternative electrolytes.

Another key area for development is the architectural design of the system's infrastructure. Due to their large size, flow batteries are not sealed units, unlike lithium and sodium-ion cells. This means that if constructed in a modular fashion, elements of the system's infrastructure can be interchanged based on application demand. Numerous specific areas can be investigated for flow batteries; electrolyte size, pump rates, electrolyte storage and electrode interface size are a few examples. These infrastructural changes should be considered with the novel electrolyte investigations, as there will likely be symbiotic properties for investigating both areas concurrently. This is especially relevant for the UK, given the variety of energy generation and will be well placed to complement the UK's flexible grid.

Metal-air batteries, including zinc-air and lithium-air batteries, offer unique performance characteristics. They exhibit relatively fast response times (lower than lithium and sodium-ion) and can support long discharge durations, making them suitable for specific grid flexibility applications. However, challenges remain in optimising their round-trip efficiency.

Metal-air batteries have garnered significant interest in recent years as a potential solution for large-scale and long duration energy storage. As the technology operates using oxygen from the air (as a cathode), high theoretical energy densities can be achieved. However, current challenges related to efficiency, cost, and durability hinder widespread deployment. In a similar manner to flow batteries, this technology has not benefitted from the high level of research and development that technologies aligned to EV applications have received. As such, the technology is well positioned to benefit from further research and development into new materials that can enhance the efficiency of the oxygen reduction reaction (ORR).

A good example of the commercial application of metal-air batteries is observed with another US-based firm, Form Energy. The company is leading the development of metal-air batteries, with a commitment to build multiple plants. Most recently, it announced plans to develop a metal-air battery in Georgia, with a duration of 100 hours at 15MW. Form Energy has opted to use Iron-air batteries which significantly reduces the cost of the battery, given iron is a relatively cheap material.

In addition to battery technology, there are BESS research opportunities examining performance and lifespan optimisation, investigating responsible recycling practices and harnessing the potential of second-life batteries.

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[30] ESS Inc. Life-cycle analysis introduction.

Battery management systems provide a potential route to integrating current and next-generation innovations at the cell-to-pack level, whilst preserving vital performance and safety characteristics that are inherently lost in most current battery pack designs.

All battery systems will require a redesign and validation of battery packs and electronics at scale to accommodate the quantum upgrade at the cell-level, specifically the electrolyte and anode. Current lithium-ion technologies, with the notable exception of LFP, generally suffer from inefficient "cell-to-pack" designs; innovations in cell-to-pack for LFP are leading to increased thermal stability range, thus greater safety and preservation of pack energy. The cell design benefits from the fact that 200 Wh/kg could be achieved whilst improving thermal stability at a relatively low cost.

Furthermore, when utilising solid-state electrolytes, there is potential for module-less designs, whilst preserving gravimetric density (e.g., around 70-80% from cell-to-pack). The key barriers are stack pressure, working temperature and swelling. Lithium metal, for example, may encounter around a 10-15% decrease in volumetric energy density due to swelling (lower for silicon), but it should stay relatively contained within stack pressure, growing at around 5 micron/mAh/cm^2 of cathode loading. Therefore, any research efforts could focus on the impact of breathing and swelling on stack pressure to understand the opportunities of cell-to-pack when using solid-state electrolytes paired with silicon or lithium metal anodes.

Battery management systems, while researched in EV, are receiving less attention in BESS. Further research could explore:

- Developing algorithms for predicting battery degradation, improving thermal management systems, and developing advanced control systems for battery charging and discharging in real-time across different BESS applications while considering factors such as energy prices, weather patterns, and grid demand.
- Investigating control systems that can effectively manage the variability of renewable energy sources and exploring the use of predictive modelling techniques to anticipate changes in energy production and consumption, to adjust the operation of BESS accordingly.
- Developing control systems that can detect and respond to potential issues and facilitate safe shutdown and restart of BESS plants, exploring advanced monitoring and diagnostic systems that can identify potential issues and enable preventative maintenance, reducing the risk of unplanned downtime.
- Developing thermal management systems that could focus on more passive forms of heating through the removal of liquid cooling, which might also result in cheaper packs.

Systems level research is becoming increasingly vital for BESS, including areas such as safety, efficiency improvements and enabling V2G (Vehicle-to-Grid). As well as research addressing safety issues at a materials level, more work is needed to improve the response and lower the cost of systems level safety structures for large scale BESS. Efficiency improvements are also needed at larger scales, as even small improvements are meaningful at the giga-scale. Finally, understanding the potential for V2G and developing working systems that ensure reliable storage capacity could be the focus of future research.

Summary

Research opportunities span various aspects of battery technologies, including the optimisation of LFP and sodium-ion batteries, the development of flow batteries, and the exploration of metal-air batteries for large-scale energy storage. Research in related areas such as battery management systems and ancillary areas, including battery recycling and the utilisation of second-life batteries, is also needed. This research will help to enhance battery longevity, battery cost, and battery performance, thereby improving grid integration and flexibility.

The security of supply is crucial, as UK BESS operators seek to diversify their supply chains and qualify new entrants outside the currently monopolised (and bottlenecked) midstream of China. Global cell producers must guarantee reliable short- and long-term access to high-quality battery feedstock material. This is particularly important given the expected supply deficits of critical battery metals over the next decade and the potential strain on financial margins and supply security.

The anticipated tightening of European legislation will determine the rules of origin for battery raw materials, which will impact supply chain decisions and geographical coverage. Legislation mechanisms are expected to incentivise local manufacturing and support the increase in UK renewable capacity targets. In addition, the overall UK electricity market will need reform, to meet the complex requirements of flexibility generation, as key electricity supply chain stakeholders look to develop innovative revenue streams.

Long-term research, combined with relevant policy and legislation, is needed to advance sustainable and efficient energy storage solutions in the UK. The integration and long-term coordination of these activities will help to ensure a resilient and sustainable energy future.

Glossary

Abbreviation	Term
BEIS	Department for Business, Energy & Industrial Strategy (currently referred to as Department for Energy Security and Net Zero)
BESS	Battery Energy Stationary Storage
BoM	Bill of Materials
BTM	Behind the Meter
°C	Degree Celsius
CAES	Compressed Air Energy Storage
CAM	Cathode Active Materials
CAPEX	Capital Costs
CCGT	Combined Cycle Gas Turbine
CFD	Contracts for Difference
CO_2	Carbon Dioxide
ESG	Environmental, Social, and Governance
ESO	Electricity System Operator
ESS	Energy Stationary Storage
EV	Electric Vehicle
GBP	Pound sterling
GW	Gigawatt
GWh	Gigawatt hour
hr	Hour
kg	Kilogram
KPI	Key Performance Indicator
kW	Kilowatt
kWh	Kilowatt hour
L	Litre
LAES	Liquid Air Energy Storage
LCC	Life cycle Cost
LCE	Lithium Carbonate Equivalent
LCOS	Levelised Cost of Storage
LFP	Lithium Iron Phosphate
Li	Lithium
LTO	Lithium Titanium Oxide
mAh/g	Milliampere-hours per Gram Mass
min	Minutes
ms	Millisecond
MtCO2	Metric tons of carbon dioxide
MW	Megawatt
MWe	Megawatt electricity
MWh	Megawatt hour
Na	Sodium
NCA	Lithium Nickel-Cobalt-Aluminium Oxide
NMC	Nickel Cobalt Manganese
N/P	Ratio of Anode and Cathode
NMP	N-Methyl Pyrrolidone
OCGT	Open Cycle Gas Turbine
OPEX	Operational Cost

PBA	Prussian Blue Analogues
PHS	Pumped Hydro Storage
REMA	Review of Electricity Market Arrangements
s	Second (time)
SLB	Second Life Batteries
Si	Silicon
TWh	Terawatt hour
UPS	Uninterruptible Power Supplies
US$	United States Dollar
V	Voltage
Wh	Watt hour

Key Terms

1. **Batteries Overview**

In conventional terms, a battery is a means of storing energy; whilst definitions vary, it is commonly termed that a battery stores energy through a means of a (reversible) chemical reaction. At an industry scale, batteries are usually made from a collection of cells, a singular unit within which the chemical reactions occur. There are notable parts to a cell:

a. Cathode. One of the two electrodes within the cell, which discharges electrons during charge and receives electrons during discharge. The battery community commonly refers to the positive electrode in a rechargeable battery as the cathode, regardless of whether the battery is being charged or discharged.

b. Anode. The second electrode within the cell, which discharges electrons during discharge and receives electrons during charging. The battery community commonly refers to the negative electrode in a rechargeable battery as the anode, regardless of whether the battery is being charged or discharged.

c. Electrolyte. Substances that facilitate the flow of ions between the cathode and anode in a battery.

d. Separator. An impermeable layer that allows for ions to transfer through, without which the cell would short circuit.

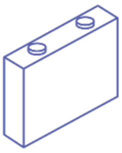
2. **Cell Format**

Cell formats are not widely discussed but play an important role in battery design and performance. Principally, three formats exist:

e. Cylindrical. Typically made using a tightly wound coil pack of electrodes and separators.

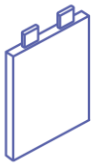
Pros	Cons
Rigid, preventing swelling	Prone to thermal runaway, due to lack of surface heat transfer
High Power for Size	

f. Prismatic. Can be made from either wound or stacked electrodes.



Pros	Cons
Space efficient stacking	Electrode winding is space inefficient, leaving empty spaces within the cell
Can become a structural part, when of sufficient size	

g. Pouch. Typically made from stacked layers of electrodes



Pros	Cons
Space efficient due to thin shape	Weakest of the cell format and can be prone to piercing
Good heat transfer and allows for swelling	

3. Cell Technologies

A broad range of technologies for batteries exist. Frequently, batteries can be grouped by the type of electrolyte they use, for example, lithium-ion. However, this is considered an umbrella term, as it is possible to classify further nuanced differences within each. For lithium-ion batteries, technologies are referenced by the type of chemistry used at the cathode, but exceptions to this do exist.

The choice of chemistry depends on a variety of factors, some of these include (non-exhaustive); end user application, cost, raw material supply availability, cyclability and energy density. The below table outlines and explains a non-exhaustive list of the chemistries discussed in this report.

Technology	Description
Lithium Iron Phosphate ($LiFePO_4$)	The most favoured BESS technology due to low cost and high cyclability.
Nickel Manganese Cobalt ($LiNi_xMn_xCo_{1-x-y}O_2$)	Can be broken down further into different types of stoichiometry (e.g. 622, 811 etc). Less applicable for BESS due to lower cycle life, and higher costs.
Lithium Cobalt Oxide ($LiCoO_2$)	Unsuitable for BESS, due to low cycle life and cost, predominantly used in consumer electronics.
Sodium-Ion	Use sodium (Na) instead of lithium (Li) as the electrolyte. In the early stages of development. Three types of cathodes exist: Layered Transition Metal Oxide, Polyanion and Prussian Blue Analogues.
Flow batteries	Vanadium is the preferred chemistry increasing in popularity for Zinc Iron and Zinc Bromine. Flow batteries have a long lifetime and are scalable. Present as one, very large cell, rather than a collection of smaller cells.
Metal-air	Like flow batteries, metal air are large scale. They store energy through a reversible oxidation process. Metal-air batteries provide the option for long term energy storage at potentially low costs.
Solid-state batteries	Often termed as a 'holy grail' for batteries, Solid-state batteries are so called due to the electrolyte being solid rather than liquid. These batteries hold the potential to offer excellent energy density and cycle life but currently require further development for commercial viability.

4. Discharge Duration

Discharge duration is a key feature of energy storage. No fixed term for duration exists, but the term duration is frequently misconstrued. However, it typically refers to discharge duration, which is the amount of time a system can produce energy, which it has previously stored at the rated power. The typical units for grid scale applications are MW or GW.[31]

5. Storage Duration

Storage duration refers to the length of time that a specific energy storage system can retain the energy it has accumulated. Generally, as time progresses from the point of energy capture, the ability of the system to maintain stored energy diminishes across all types of storage technologies.

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[31] AFRY (2022). Benefits of Long Duration Electricity Storage: A Report to BEIS. 1-22 (https://www.gov.uk/government/publications/benefits-of-long-duration-electricity-storage)

Annexes

Annex I. Cell Cost Model Assumptions and Scenarios

Table 14. Cost model assumptions

Component	Active material	Current specification	Optimised (target) specification
Cathode	NMC811, LFP	Energy density: LFP 170Wh/kg, NMC 275Wh/kg	Energy density: LFP 240Wh/kg, NMC 330Wh/kg
	Sodium-ion	Energy density: 100Wh/kg	Energy density: 140Wh/kg
	Cathode loading	Values accepted between 1.5 and 6.0 mAh/cm^2; assumed for cells designed for EV; lower end assumed for power cells, 1.5-2.5mAh/cm^2; 3mAh/cm^2 is the practical limit for LFP; 4.0-4.5 mAh/cm^2 is the best in-class EV cell	No specific target
Anode	Graphite	Natural graphite 360 mAh/g, Synthetic graphite 345 mAh/g	
	Graphite-Silicon	Assumed 5% Si additive (current state-of-the-art is around 7%)	15% Si additive
	Silicon	Pre-lithiation assumed on silicon-dominant anodes to compensate for lithium loss	Fully-utilised and expensive Si
	Li-metal	Cheap CVD: 5µm of Li, assumed to be from a chemical vapour deposition (CVD) process without a sacrificial layer Rolled Li: 40µm, 20µm per layer, no Cu foil	Expensive: 5µm of Li, assumed to be from a more exotic deposited anode process, double-sided with Cu foil backing
	Hard carbon	350 mAh/g	No specific target
Electrolyte	Sulphide	Catholyte content: 30% conservative; anolyte content: 50%	Catholyte content: 10-20%; anolyte content: 10-30%
	Oxide	Catholyte content:	Catholyte content:
	Polymer	Catholyte content: 25% conservative; anolyte: 40%	Catholyte content: 10-15%
Separator	Sulphide	Thickness: 40µm	Thickness: 20µm
	Oxide	Thickness: 50µm (state-of-the-art)	Thickness: 20µm
	Polymer	Thickness: 40µm	Thickness: 20µm

Table 15. Modelled scenarios summary

Model No.	Cathode	Anode	Electrolyte	Separator thickness (μm)	Note
1	NMC811	Graphite	Liquid	NA	Baseline comparison, deployed in EV & ESS
2	NMC811	G-Si	Liquid	NA	Si 5% blend - high-performance state-of-the-art cells
3	NMC811	Si	Liquid	NA	
4	NMC811	Si - micro, fully utilised	Liquid	NA	Optimised Si-anode
5	NMC811	Si - micro, fully utilised	Oxide	50	Si-anode with oxide solid-state electrolyte
6	NMC811	Si - micro, fully utilised	Oxide	20	Optimised Si-anode with thinner separator
7	NMC811	Li-metal (rolled)	Oxide	50	
8	NMC811	Li-metal (rolled)	Oxide	20	Optimised rolled lithium metal anode with thinner separator
9	NMC811	Li-metal (CVD)	Oxide	50	
10	NMC811	Li-metal (CVD)	Oxide	20	Optimised deposited lithium metal anode with thinner separator
11	NMC811	Anode-less	Oxide	50	Industry analogue: Quantumscape
12	NMC811	Anode-less	Oxide	20	
13	NMC811	Si - micro, fully utilised	Sulphide	40	Industry analogue: Solid Power
14	NMC811	Si - micro, fully utilised	Sulphide	20	Industry analogue: Solid Power
15	NMC811	Li-metal (rolled)	Sulphide	40	
16	NMC811	Li-metal (rolled)	Sulphide	20	Optimised rolled lithium metal anode with thinner separator
17	NMC811	Li-metal (CVD)	Sulphide	40	
18	NMC811	Li-metal (CVD)	Sulphide	20	Optimised deposited lithium metal anode with thinner separator
19	NMC811	Anode-less	Sulphide	40	
20	NMC811	Anode-less	Sulphide	20	Optimised anode-less with thinner separator
21	NMC811	Si - micro, fully utilised	Polymer	40	
22	NMC811	Si - micro, fully utilised	Polymer	20	
23	NMC811	Li-metal (rolled)	Polymer	40	Industry analogue: Blue Solutions (Bollorè)
24	NMC811	Li-metal (rolled)	Polymer	20	Optimised but with no obvious route to scale up
25	NMC811	Li-metal (CVD)	Polymer	40	
26	NMC811	Li-metal (CVD)	Polymer	20	Optimised but with no obvious route to scale up
27	NMC811	Anode-less	Polymer	40	
28	NMC811	Anode-less	Polymer	20	Optimised anode-less with thinner separator
Model No.	Cathode	Anode	Electrolyte	Separator thickness (μm)	Note
29	LFP	Graphite	Liquid	NA	Baseline comparison, deployed in EV & ESS
30	LFP	G-Si	Liquid	NA	Si 5% blend - high-performance state-of-the-art cells
31	LFP	Si	Liquid	NA	
32	LFP	Si - micro, fully utilised	Liquid	NA	Optimised Si-anode
33	LFP	Si - micro, fully utilised	Oxide	50	Si-anode with oxide solid-state electrolyte

34	LFP	Si - micro, fully utilised	Oxide	20	Optimised Si-anode with thinner separator
35	LFP	Li-metal (rolled)	Oxide	50	
36	LFP	Li-metal (rolled)	Oxide	20	Optimised rolled lithium metal anode with thinner separator
37	LFP	Li-metal (CVD)	Oxide	50	
38	LFP	Li-metal (CVD)	Oxide	20	Optimised deposited lithium metal anode with thinner separator
39	LFP	Anode-less	Oxide	50	Industry analogue: Quantumscape
40	LFP	Anode-less	Oxide	20	
41	LFP	Si - micro, fully utilised	Sulphide	40	Industry analogue: Solid Power
42	LFP	Si - micro, fully utilised	Sulphide	20	Industry analogue: Solid Power
43	LFP	Li-metal (rolled)	Sulphide	40	
44	LFP	Li-metal (rolled)	Sulphide	20	Optimised rolled lithium metal anode with thinner separator
45	LFP	Li-metal (CVD)	Sulphide	40	
46	LFP	Li-metal (CVD)	Sulphide	20	Optimised deposited lithium metal anode with thinner separator
47	LFP	Anode-less	Sulphide	40	
48	LFP	Anode-less	Sulphide	20	Optimised anode-less with thinner separator
49	LFP	Si - micro, fully utilised	Polymer	40	
50	LFP	Si - micro, fully utilised	Polymer	20	
51	LFP	Li-metal (rolled)	Polymer	40	Industry analogue: Blue Solutions (Bollorè)
52	LFP	Li-metal (rolled)	Polymer	20	Optimised but with no obvious route to scale up
53	LFP	Li-metal (CVD)	Polymer	40	
54	LFP	Li-metal (CVD)	Polymer	20	Optimised but with no obvious route to scale up
55	LFP	Anode-less	Polymer	40	
56	LFP	Anode-less	Polymer	20	Optimised anode-less with thinner separator

Model No.	Cathode	Anode	Electrolyte	Separator thickness (µm)	Note
57	Na-ion	Hard carbon	Liquid (Na-ion)	NA	Faradion, pilot- scale
58	Na-ion	Hard carbon	Liquid (Na-ion)	NA	Faradion, future scaled to 10GWh
59	Na-ion	Hard carbon	Liquid (Na-ion)	NA	Power cell; industry analogue: Natron Energy
60	Na-ion	Hard carbon	Liquid (Na-ion)	NA	Power cell; industry analogue: Natron Energy
61	Na-ion	Hard carbon	Liquid (Na-ion)	NA	Higher energy density cell
62	Na-ion	Hard carbon (optimised)	Liquid (Na-ion)	NA	Higher energy density cell, with cheaper anode
63	Na-ion	Hard carbon (optimised)	Liquid (Na-ion)	NA	Higher energy density cell, with optimised anode and electrolyte

Source Rho Motion Cell Cost Model

Annex II. International Developments in Legislation

European Legislation

The EU Battery Passport and Fit for 55 Carbon Border Adjustment Mechanism are expected to incentivize local manufacturing, while the RePowerEU plan is expected to increase renewable capacity targets, driving additional capacity. Net Zero emissions legislation will also accelerate targets to electrify EV fleets and switch to renewable energy sources to power electricity grids.

Several BESS legislative documents have been composed in recent years in Europe, although many of these are still under development and aligned principally to EVs and cell manufacturing. The European Council is set to participate in the COP26 Climate Summit in November 2023 to encourage nations to announce their Nationally Determined Contributions (NDCs) or 2030 climate targets in line with the Paris Agreement. Additionally, the EU aims to increase international climate finance while also supporting developed countries. The European Green Deal, which calls for all 27 EU Member States to commit to achieving Net Zero emissions by 2050, with intermediate targets to reduce greenhouse gas emissions by 55% by 2030 compared to 1990 levels, has also been announced. On July 14th 2021, the EU Commission revealed the Fit for 55 package, which includes 13 proposals for climate change legislation to meet the greenhouse gas emission reduction targets. The package includes the tightening of the EU Emissions Standards Trading Scheme, carbon border tariffs, and the phasing out of ICE vehicle sales by 2035.

The proposed revision of the European Energy Tax Directive is expected to improve the regulatory environment for energy storage. Currently, double financial charging regimes have hindered investment in storage technologies in some countries, such as Germany. However, the revision of the directive will reclassify energy storage as redistributors from January 2023, resulting in a single charge for either drawing or supplying power. While the Netherlands has already eliminated the double taxation law, storage assets in the country still face difficulties due to their classification as a consumer of the electricity grid, which makes them liable for grid usage fees.

North American Legislation

In January 2021, President Biden issued an executive order to tackle the climate crisis, putting it at the forefront of US foreign policy and national security, and committing the US to achieve Net Zero emissions by 2050. During his Leaders Summit on Climate in April 2021, he announced a new goal to reduce greenhouse gas emissions by 50-52% below 2005 levels by 2030. While there are currently no direct national targets for renewables, President Biden has set a goal for a carbon pollution-free power sector by 2035.

Starting in 2023, the Inflation Reduction Act's investment tax credits will apply to standalone energy storage assets charging directly from the grid, not just those paired with solar. This could potentially increase investment in energy storage and facilitate a wider range of services to the grid. A COVID-19 relief package passed in December 2020 includes $1 billion for research, development, and demonstration of energy storage technology over the next five years. President Biden also plans to double annual public climate financing to developing countries by 2024.

Additionally, in August 2021, the Senate passed the bipartisan infrastructure bill, which includes a recommendation for a US$73 billion investment in the grid, including US$11 billion for grid resilience and US$3 billion for enhancing grid flexibility. The bill also creates a new Grid Deployment Authority to build a reliable, modern grid.

On a state level, renewable mandates have been set in most US states, and some have also adopted energy storage mandates. California, for example, has set a renewable mandate of 50% by 2025, 60% by 2030, and 100% carbon-free by 2045. It also has a storage mandate of 1,325MW by 2020, of which 500MW is to be distribution-connected and installed by the state's three largest utilities. California offers financial incentives, such as the Self-Generation Incentive Program, which provides incentives to support existing, new, and emerging distributed energy resources. From 2017-2021, $378 million has been set aside for customer-sited energy storage projects, with storage-plus-solar receiving priority over standalone energy storage firms. In 2018, customers with energy storage systems were allowed to receive credits for storage energy that is sent back to the grid if charged entirely from solar.

There is currently no federal target for energy storage in the United States. However, the US Energy Storage Association (ESA), a national trade association focused on energy storage with over 190 members including utilities and energy companies, has set a goal of deploying 100GW of storage by 2030.

Chinese Legislation

In September 2021, the State Council of China released a document outlining the plan for reaching carbon neutrality by 2060. The plan includes a target of 20%, 35%, and 80% non-fossil fuel energy consumption by 2025, 2030, and 2060, respectively. The document emphasizes the importance of promoting the development of new types of energy storage, including BESS and hydrogen energy. In July 2021, China also set a national energy storage target of 30GW by 2025. Furthermore, all regional authorities have included renewable energy and energy storage in their local energy development plans. Based on local policies, an estimated 1,200GW of new renewable energy could lead to 120GW of new energy storage capacity in the Greater China region. The National Energy Administration has also released new requirements for large-scale BESS projects, including a ban on certain types of batteries and the need for consistent screening and safety assessment when selecting second-life EV batteries.

Qinghai was the pioneer in launching an ESS subsidy program in China. Following their lead and the encouragement of the State Council, other provinces are currently in the process of publishing draft subsidy programs. While there are some large national demonstration projects, most ESS projects are small and rely on renewable energy projects.

Annex III. About Rho Motion, the Faraday Institution and the Faraday Battery Challenge

This report was written by Rho Motion and commissioned by the Faraday Institution as part of the Faraday Battery Challenge.

About Rho Motion

Rho Motion offers the most comprehensive and well-informed forecasts and analysis for the energy transition. Our core assessments, databases and outlooks provide actionable intelligence on the development of electric vehicle, battery, charging and infrastructure markets. We consider the implications of government legislation and incentives, OEM and battery manufacturer strategy, in addition to raw material, technology and infrastructure costs, capital investment and consumer behaviour.

Headquartered in London, our team has expertise in vehicle markets and economics, the battery supply chain and its raw materials, as well as the impact of government legislation on OEM technology choices.

Rho Motion tracks project announcements for the BESS market, with a database of over 2,000 battery grid-scale storage projects globally. The short-term (i.e., two years) outlook for the grid ESS market considers project and capacity announcements, while the long-term (i.e., greater than five years) outlook considers the key drivers of the market, for example increasing global electricity demand, increasing share of renewables, and deployment of battery chemistries that will meet future demand.

About the Faraday Institution

The Faraday Institution is the UK's independent institute for electrochemical energy storage research, skills development, market analysis, and early-stage commercialisation. Bringing together expertise from universities and industry, the Faraday Institution endeavours to make the UK the go-to place for the research and development of new electrical storage technologies for both the automotive and wider relevant sectors. Headquartered at the Harwell Science and Innovation Campus, the Faraday Institution is a registered charity with an independent board of trustees, and a delivery partner for the Faraday Battery Challenge.

About the Faraday Battery Challenge

The Faraday Battery Challenge at UK Research and Innovation is delivered by Innovate UK. The Challenge is making the UK a science and innovation superpower for batteries, supporting the UK's world-class battery facilities along with growing innovative businesses that are developing the battery supply chain for our future prosperity. Its aim is to build a high-tech, high-value, high-skill battery industry in the UK.

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