



# Powering the Future

Horizon scanning for emerging technologies and breakthrough innovations in the field of mid- to long-duration energy storage

2026

## HIGHLIGHTS

- ▶ This **Horizon Scanning** exercise was developed to support the **European Innovation Council** strategic intelligence in the field of **mid- to long-duration energy storage**. **Horizon Scanning is a qualitative foresight method**, aimed, in this context, at the early identification of technology and innovation developments across all technology readiness levels before their potential is widely recognised.
- ▶ **Several core technologies** were prioritised by workshop participants across different energy storage fields. These include solutions such as solid-state, sodium-ion and flow batteries, as well as innovations such as the Carnot battery, the battolyser architecture, thermophotovoltaic heat batteries, and incremental innovations in pumped storage hydropower.
- ▶ Additionally, a range of **enabling technological and innovation** areas were identified as key to advancing the field. These include, but are not limited to, developments in IT, CRM-free and recyclable membranes, compact heat exchange units, microwave and plasma heating systems, thermal integration systems, and second-life batteries for hybridisation.
- ▶ **Contextual factors** shaping the development of energy storage were identified across social, technological, economic, environmental, and policy domains. These include infrastructure readiness; circularity, recycling, and end-of-life management; environmental impacts of infrastructure; and regulatory frameworks and permitting.
- ▶ **The conclusions highlight that mid- to long-duration energy storage is evolving towards a diversified and interconnected portfolio of complementary technologies**, whose successful deployment depends not only on technical advances but also on enabling policy frameworks, system conditions, and increasing convergence of broader technological developments.

*'The voltaic battery was an alarm-bell to experimenters in every part of Europe.'*

Humphry Davy

## Foreword

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The quote by Humphry Davy captures how breakthroughs in energy technologies can trigger waves of experimentation and discovery. Following Volta's invention of the first practical electrochemical battery in 1800<sup>1</sup>, scientists across Europe gained, for the first time, a reliable source of continuous electric current, instead of quick bursts.

This development greatly accelerated research in electricity, chemistry and electrochemistry and enabled a wide range of new experimental approaches. And it illustrates how advances in one technological domain can act as catalysts for broader scientific and technological progress, often enabling innovations far beyond their original purpose.

While the history of energy storage is marked by electrochemical systems, the field has evolved into a much broader technological landscape. Research and innovation within the domain now includes a wide range of approaches, including thermal, mechanical and hybrid storage systems.

Each of these technologies addresses different operational needs and timescales within the energy system, reflecting the growing complexity of integrating renewable energy sources and ensuring system flexibility.

## Introduction

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### Project and report context

This document reports on the conclusions of a Horizon Scanning exercise developed in the context of the project FUTURINNOV (FUTURE-oriented identification and assessment of emerging technologies and breakthrough INNOVation).

This project is a collaboration between the European

Commission's (EC) Joint Research Centre (JRC) and the European Innovation Council (EIC), the EC's flagship program for deep tech, implemented by the European Innovation Council and SMEs Executive Agency (EISMEA).

FUTURINNOV was designed to support the EIC in building strategic intelligence capacity through foresight and other anticipatory approaches. It supports activities focused on funding targets, programme design, policy feedback, and institutional governance.

The outcomes of this exercise may be used to inform future funding topics for EIC Challenges and other EC calls. They can also provide input for EIC and EC reports, as well as supporting other EU policy-making initiatives.

### Scope of the exercise and policy context

Energy storage refers to technologies and systems that capture energy produced at one time for use at a later moment [1]. Within the scope of this report, mid- to long-duration energy storage solutions (MLDES) are defined as capable of delivering energy over periods ranging from more than 8 hours to multiple days or even longer.

These systems play an important role in balancing electricity supply and demand, integrating variable renewable energy sources (RES), improving grid flexibility, enhancing the resilience of energy systems and strongly reducing the employment of fossil fuel or gas, presently used for recovering base load. Briefly, we can state that MLDES solutions will support the utilisation of RES, reduce curtailment<sup>2</sup> (which peaked at 11% in 2025 [2]), and ultimately contribute to the decarbonisation of the grid.

Storage solutions can take different technological forms, including electrochemical, mechanical, thermal, and chemical storage systems. An increasing number of hybrid solutions combine different technologies. All are increasingly recognised as a key component of the energy transition and of future climate-neutral energy systems.

The European Union (EU) has positioned energy storage as a strategic enabler of its climate and

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<sup>1</sup> The first known battery-like device is often referred to as the "Baghdad Battery," discovered in ancient Mesopotamia, nowadays Iraq, and is believed to be over 2,000 years old. However, the first true battery, known as the voltaic pile, was invented by Alessandro Volta in Italy in 1800.

<sup>2</sup> Curtailment refers to the intentional reduction of electricity generation from a source that could otherwise produce power, typically because the grid cannot absorb it at that moment. This commonly occurs with wind and solar power when: a) transmission capacity is insufficient; b) demand is low or c) system stability constraints require limiting supply.

energy objectives, particularly within the framework of the European Green Deal, which sets out a roadmap towards climate neutrality by 2050 and calls for a profound transformation of Europe's energy systems. [3]

Building on the European Green Deal, several EU policies and initiatives have further reinforced the role of energy storage. In particular, the European Commission's 2023 Recommendation on energy storage to support the deployment of storage technologies across the EU and address regulatory and market barriers. This recommendation encourages Member States to facilitate permitting procedures, ensure storage participation in electricity markets, and integrate storage into national energy planning. It emphasises the importance of storage for providing system flexibility, integrating renewable energy, and maintaining grid stability as the share of variable renewable generation increases. The initiative also highlights the need to support innovative storage technologies beyond conventional battery systems. [4]

Energy storage is further supported through broader industrial and strategic policy frameworks. Examples include the EU Battery Strategy and the Batteries Regulation, which aims to strengthen Europe's battery value chains, improve sustainability across the battery lifecycle and support large-scale manufacturing and recycling capacities. [5]

The EU already supports research and innovation in technologies within this field. Key programmes include Horizon Europe, where funding topics include long-duration energy storage systems; non-lithium stationary batteries; thermal energy storage and hydrogen-based storage. The EU also supports large storage projects through other financing instruments, such as the Innovation Fund and the Recovery and Resilience Facility (RRF).

A more recent policy development further reinforces the importance of energy storage in the clean energy transition. In March 2026, the European Commission adopted a Clean Energy Investment Strategy, aimed at mobilising the level of investment needed to achieve climate neutrality. The strategy highlights that, while public funding remains important, significantly greater private investment will be required to scale up clean energy technologies and infrastructure. This strategy includes measures to improve access to financing, support energy infrastructure such as electricity grids, and accelerate the deployment of innovative clean energy technologies. In this context, energy storage is positioned as a key enabler of system

flexibility and renewable energy integration, with the strategy contributing to more favourable conditions for its development and deployment. [6]

In the context of the EIC, a significant amount of funding is dedicated to energy systems through different Program Manager's portfolios [7]. In this sense, similar exercises to the one reported here, have covered topics such as advanced materials for energy [8] and solar fuels and chemicals [9]. Following these, the present report supports the EIC strategic intelligence on Advanced Materials for Energy, but with a focus on a specific scope of energy storage solutions.

Hydrogen-based solutions are already significantly supported by the EIC and other EU funding mechanisms. This exercise therefore sought to broaden the range of technologies considered, particularly across thermochemical, thermal, mechanical, and hybrid storage approaches. For this reason, the JRC and the EIC decided not to consider hydrogen as a standalone solution within the scope of the exercise, while still covering hybrid systems in which hydrogen constitutes a key component.

## Methodology

**Horizon Scanning** is a qualitative foresight method which is aimed at the early discovery of developments not yet on the radar of most experts, decision makers, or the general public, and whose potential is not yet widely recognised. It is not a predictive tool, rather it encourages the exploration of novelties that offer opportunities and challenges in the medium or long-term. [10, 9, 11]

FUTURINNOV includes a series of thematic workshops that follow a tailor-made approach to this methodology. This approach uses a participatory detection, clustering, and sense-making process for signals, trends and contextual factors related to emerging technologies and breakthrough innovations. Each workshop is dedicated to a specific EIC Programme Manager's portfolio, or a domain deemed of interest by the EIC. [12]

**Trends and signals** are captured through a series of participatory exercises preceded by qualitative desk research, as well as data and text mining. They originate from a diversity of sources, ranging from scientific publications, patents and previously funded projects to institutional websites, news, online

articles and other media.<sup>3</sup>

During each workshop, through a specific methodology composed of several analytical and selection steps (by voting), participants converge on a priority list of topics.<sup>4</sup>

The criteria for this selection include relevance to the exercise's scope, potential impact and overall novelty across all technology readiness levels. The final topics include technologies and innovations, as well as relevant contextual factors for their development and uptake.

This report refers to a workshop held online on 04 February 2026. The workshop was held with a group of selected experts from academia, research and technology, business, business associations, consultancy and policy-making organisations.

This diversity of institutional backgrounds, as well as various fields of specific expertise, was key to bringing different perspectives to the conversation. The resulting collective intelligence helped to build significant insights around the emerging technology landscape in the field.<sup>5</sup>

## Quick guide

This report is organised in 3 sections:

- **trends and signals** on technologies and innovations.
- **contextual factors**, covering drivers, enablers and barriers related to the development and uptake of those technologies and innovations.
- **conclusions** providing complementary insights and overarching analysis.

## Trends and signals

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The trends and signals presented in this section were identified by participants as the most relevant within the scope of the workshop. They are organised in two clusters:

- A. Core energy storage technologies and innovations** - solutions that directly provide energy storage and conversion capacity, such as electrochemical, thermal, mechanical, or hybrid storage systems enabling medium- and long-duration energy storage (LDES).
- B. Enabling technologies and innovations** - solutions that support, optimise, or extend the performance, scalability, and integration of core storage technologies, including materials, components, digital tools, and system architectures that improve efficiency, durability, safety, and grid integration.

This clustering reflects the methodology applied in the pre-workshop signal analysis and in the assessments conducted by participants during the online workshop.

It distinguishes between domain-specific technologies, such as specific types of batteries and systems, and technologies or components whose enabling or enhancing role makes them key to the deployment and innovation of the core technologies.

Within each cluster, signals are further organised into sub-clusters corresponding to broader families of energy storage technologies and related fields:

1. Electrochemical
2. Thermal
3. Mechanical
4. Hybrid

These sub-clusters reflect both the structure of the breakout groups during the workshop and the

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<sup>3</sup> The understanding of what constitutes a signal or a trend may vary [125, 126]. As it is not yet consensual, for the purposes of this project both are relevant and understood as tangible manifestations of novelty in science, technology, innovation, markets, media, and other fields. They can cover different maturity levels from basic research to commercial readiness. Although often used interchangeably, a signal is less consolidated than a trend.

<sup>4</sup> For this exercise, the JRC and the EIC compiled and assessed a longlist of 103 trends and signals for their relevance to the workshop's scope and objectives. The list was later reduced to 80, by removing out of scope or less relevant topics. From this shortlist, the JRC extracted specific technologies and innovations (often more than one per signal), removed repetitions and overlaps, and organised them into two clusters: A. core energy storage technologies and B. enabling technologies. These two curated lists formed the basis for the workshop discussions. Participants reviewed the lists in separate steps, added additional relevant or previously overlooked topics, grouped and linked related issues, and ultimately converged on a final set of topics for both clusters, summarised in this report. The final topics are presented together with the bibliographic references of the signals collected before the workshop, supplemented where necessary with additional desk research carried out after the workshop.

<sup>5</sup> For more detailed information on the current development status of several of the technologies discussed in this document, the authors suggest, among other references, consulting the publications of the EU's Clean Energy Technology Observatory (CETO) [129], in particular the recently published 2025 status report on battery technology. [128]

different areas of expertise represented.

For the purpose of this exercise, it was neither meaningful nor methodologically sound to compare or rank fundamentally different storage technologies against one another, as they typically serve distinct functions and application domains.

Experts were therefore grouped by technological field to enable in-depth discussion within each domain. With the exception of hybrid or cross-cutting solutions, discussions were necessarily limited to areas in which participants had direct expertise. Groups were formed according to the number of experts available and the signals collected.

Two groups focused on electrochemical storage, one on thermal storage, and one on mechanical and hybrid solutions. This distribution is also reflected in the number of final results, with some areas presenting more topics than others. The authors consider this as a reflection of the asymmetric nature of the research and innovation landscape within the field.

**Figure 1.** An AI generated image depicting the coupling of renewable energy and energy storage



Source: Adobe Stock (stock.adobe.com)

## A. Core energy storage technologies

### A.1 Electrochemical

#### A.1.1 - Solid state batteries

Solid-state batteries primarily replace the liquid electrolytes<sup>6</sup> used in conventional lithium-ion batteries with solid electrolytes. This shift aims to address key limitations of current systems,

particularly safety risks, energy density constraints, and long-term durability.

The term “solid-state” refers specifically to the electrolyte material and does not replace existing cathode chemistries. Instead, solid electrolytes can be paired with established cathode materials such as lithium iron phosphate (LFP) or nickel–manganese–cobalt (NMC) variants.

Rather than converging on a single dominant material, the field is evolving into a diverse landscape in which different electrolyte classes address specific performance constraints.

Most current innovations in the field of solid-state electrolytes focus on design and interface engineering. Halide electrolytes offer improved chemical stability and better compatibility with high-voltage cathodes, but suffer from interfacial instability. Argrodite electrolytes achieve very high lithium-ion conductivity due to their favourable crystal structures, but they introduce handling and manufacturing challenges, including issues related to hydrogen sulphide (H<sub>2</sub>S) generation and the need to ensure worker safety, which in turn increases cost and process complexity. In addition, various other solid electrolytes are being developed, including polymer, oxide-based, and hybrid, all with their own characteristic advantages and disadvantages.

Other research directions focus on long-cycle electrolytes designed to suppress dendrite formation<sup>7</sup> and maintain stable electrochemical interfaces during extended battery operation.

These developments create several potential advantages across energy-storage applications:

- Potential safety benefits by eliminating flammable liquid electrolytes and reducing leakage risks, while recent incidents show solid-state batteries can still experience severe failures if design or manufacturing issues arise.
- Higher energy density, in particular for solid-state cells that can reliably use lithium-metal or other alkali-metal anodes, alongside high-voltage cathodes, provided interface stability can be maintained.
- Longer operational lifetimes through electrolyte systems engineered for stable long-term cycling.

<sup>6</sup> Electrolytes are the materials inside a battery or other electrochemical storage device that let charged particles (ions) move between the two electrodes while blocking electrons. This internal “ion highway” is essential for charging and discharging, and its composition strongly influences performance, safety, and lifetime, especially in advanced long-duration storage technologies.

<sup>7</sup> Dendrite formation refers to the growth of tiny, tree- or needle-like metal structures inside a battery, usually on the anode, during charging. These protrusions can pierce the separator between electrodes, causing internal short circuits, faster ageing, and, in extreme cases, safety failures, which makes controlling dendrites crucial for next-generation high-energy and long-duration batteries.

- Application-specific optimisation remains important, with stationary storage applications being more cost-sensitive, although developments in adjacent sectors such as electric vehicles may influence positively cost and performance trajectories.

Despite this progress, several challenges remain before large-scale deployment is possible:

- Persistent interfacial resistance and degradation between solid electrolytes and electrodes, particularly when paired with lithium-metal anodes.
- Manufacturing scalability and cost control across different electrolyte chemistries, including process choices and production yields when moving from pilot to industrial scale (for example dry or aqueous processing routes).
- Trade-offs between ionic conductivity, mechanical strength, and electrochemical stability.
- Material availability and sustainability constraints for some electrolyte compositions.

Sources: [13, 14, 15, 16, 17, 18, 19, 20, 21, 22]

### A.1.2 - Sodium ion

Energy storage research is increasingly shaped not only by performance improvements, but also by constraints related to material supply and manufacturing capacity.

Several signals highlight developments in sodium-based battery technologies and their associated supply chains. These developments span multiple technological pathways, including advanced electrolytes and new sodium-based battery concepts. Together, they illustrate approaches that could reduce dependence on certain critical raw materials (CRM)<sup>8</sup> while influencing several stages of the energy-storage value chain.

Participants also emphasised that, for very large-scale grid deployment, the availability of lithium could become a limiting factor, positioning sodium-based systems as a complementary or alternative option.

These developments create several opportunities across the energy-storage system:

- Reduced dependence on some CRM, which could improve supply security and lower exposure to geopolitical or market disruptions.
- More flexible and potentially shorter value chains, supported by the use of abundant materials such as sodium and by alternative electrolyte chemistries.
- Long service lifetimes designed for stationary storage applications, which could reduce replacement rates and cumulative material demand over time.
- New deployment models for stationary storage, including integration with renewable energy generation and—at research and pilot stages—potential coupling with water infrastructure or marine environments through concepts such as sodium-seawater batteries.

Several challenges must be addressed before these systems can be widely deployed:

- Scaling up manufacturing processes for new electrolytes and battery concepts while maintaining performance, quality, and cost control.
- Demonstrating long-term stability and operational reliability, particularly for systems using metal anodes or operating under harsh environmental conditions (e.g. wide temperature ranges, humidity, or corrosive atmospheres).
- Integrating alternative chemistries into existing industrial ecosystems, standards, and certification frameworks.
- Developing end-of-life, recycling, and reuse strategies that support the intended reductions in material criticality across the value chain.
- Addressing supply-chain bottlenecks related to anode materials, particularly the cost and availability of hard carbon or the development of viable low-cost alternatives.

Sources: [23, 24, 25, 26, 27, 28]

### A.1.3 - Flow batteries

Flow batteries are a family of electrochemical energy storage systems in which energy is stored in liquid electrolytes contained in external tanks, while the power output is determined by separate

<sup>8</sup> Critical raw materials (CRM) are metals and minerals that are both economically essential and exposed to a high risk of supply disruption. In the context of the EU, these include lithium, cobalt, nickel, graphite, and rare earth elements used in batteries and other clean-energy technologies. For mid- to long-term energy storage, they matter because dependence on a small number of countries and firms for these inputs can create price volatility, supply bottlenecks, and geopolitical vulnerabilities that affect deployment plans and costs.

electrochemical cell stacks<sup>9</sup>. This architecture decouples energy capacity (tank size) from power capacity (stack size).

Recent signals indicate renewed interest in flow batteries for mid- to long-duration stationary storage, largely driven by the growing need to integrate variable renewable energy sources into power grids and by concerns around supply-chain resilience.

Vanadium redox flow<sup>10</sup> batteries remain the most mature and widely referenced technology in this category. However, a broader range of alternative chemistries and system designs is now emerging.

Recent innovation is largely driven by this diversification beyond vanadium, including iron-based systems, zinc–bromine batteries, hydrogen–iron systems, sodium–seawater batteries, organic redox flow batteries, and related concepts such as redox fuel cells.

Workshop participants highlighted organic redox flow batteries as a particularly promising research direction, mainly because they could reduce reliance on CRM such as vanadium. Nevertheless, most experts expect that they will require more than five years to achieve significant market impact.

Across these emerging concepts, research is exploring several strategies to improve performance and reduce costs, such as using abundant or non-critical materials, adopting alternative cell configurations (for example, membraneless or tubular architectures), and developing organic or hybrid electrolytes to enhance safety, cost structure, and system design flexibility.

Flow batteries and related redox systems are being positioned for several stationary energy-storage roles:

- Utility-scale long-duration storage to balance variable renewable generation and support grid stability.
- Decentralised or off-grid storage for industrial facilities, microgrids, and remote or maritime environments.
- Niche applications where storage is integrated with additional functions, for example hydrogen handling or seawater-based energy systems.

Despite their potential, several recurring technical and system-level challenges continue to shape the development trajectory of flow batteries:

- Increasing energy density and round-trip<sup>11</sup> efficiency while maintaining the long-term chemical stability of non-vanadium electrolytes. Research directions include solid redox mediators, eutectic<sup>12</sup> electrolytes, and electrochemically active organic molecules.
- Scaling up the manufacturing of cell stacks, membranes, and alternative system architectures without reducing component lifetime or increasing system costs.
- Reducing the physical footprint of systems and simplifying auxiliary components such as pumps, tanks, power electronics, and control systems, while ensuring compatibility with existing grid infrastructure and operational practices.
- Demonstrating long-term operational reliability and predictable costs at commercial scale. For vanadium-based systems, this also includes the development of stable supply chains for vanadium electrolytes.

Sources: [29, 30, 31, 32, 33, 34, 35, 36, 37, 38]

#### A.1.4 - Metal-air batteries

Metal-based electrochemical storage is being explored as an alternative to lithium-ion batteries, with particular interest in zinc, aluminium, and iron chemistries. These systems rely on abundant materials and often use aqueous electrolytes or metal–air configurations.

<sup>9</sup> Electrochemical cell stacks are groups of individual electrochemical cells that are mechanically clamped and electrically connected (usually in series) so they operate together as one larger device. In flow batteries, fuel cells, and some other long-duration storage technologies, the stack sets the power rating (how fast energy can be delivered), while separate tanks or fuel supplies determine how much total energy can be stored.

<sup>10</sup> Redox flow batteries are a class of flow batteries in which the energy is stored in liquid electrolytes containing redox-active species that are pumped through electrochemical cell stacks. Here, “redox-active” means that the dissolved molecules or ions can reversibly gain and lose electrons during charging and discharging, allowing the battery to store and release energy many times without consuming the active material.

<sup>11</sup> Round-trip refers to a full charge–discharge cycle of a storage system and how much usable energy comes back out compared with what was put in. Round-trip efficiency (or round-trip losses) therefore captures all energy losses across charging, storing, and discharging, not just what happens inside the electrochemical cell.

<sup>12</sup> Eutectic here refers to a mixture of components combined at a specific composition that gives a lower melting point than any of the pure components, enabling liquid electrolytes at relatively low temperatures.

The main innovation does not lie in fundamentally new storage principles but in advances in materials and interface engineering, such as stabilising metal electrodes, improving air cathodes, and optimising electrolyte formulations.

Recent research has focused on stabilising metal electrodes and improving oxygen electrocatalysis<sup>13</sup> at the air cathode. In zinc systems, improved anode structuring, protective coatings, and advanced electrolyte formulations are extending cycle life and suppressing dendrite formation. These developments are supporting the first commercial zinc battery products aimed at grid applications.

Metal–air technologies are also being reconsidered as part of broader material and energy cycles. For example, aluminium–air systems could be linked to aluminium production and recycling chains, while iron–air systems are being positioned as candidates for multi-day grid balancing. Among the different options, zinc-based systems are consistently viewed as the closest to large-scale deployment.

These developments create several concrete opportunities:

- Stationary and grid-scale storage based on rechargeable zinc batteries, including zinc-ion and hybrid zinc systems, with a focus on safety, low cost, and material availability.
- Medium- to long-duration storage using zinc–air and iron–air systems, suitable for low-frequency cycling, multi-day backup, and other long-duration grid services.
- Aluminium–air primary batteries (non-rechargeable) or mechanically rechargeable batteries, integrated into aluminium-based energy-carrier cycles linked to industrial material flows. These systems have potential future applications in seasonal or remote energy storage (see Box 1).

However, several key challenges remain:

- Durability limitations in zinc batteries, including dendrite growth, hydrogen evolution, and other side reactions at the metal anode.
- Cathode and system constraints in zinc–air systems, particularly the cost, durability, and critical-material content of bifunctional oxygen catalysts.

- The low technology readiness of iron–air, aluminium–air, and related metal–air concepts. Important uncertainties remain regarding round-trip efficiency, reversibility or mechanical recharge logistics, and their practical role alongside other long-duration storage technologies such as sodium-ion batteries (see A.1.2), flow batteries (see A.1.3), lithium-ion systems, and hydrogen-based storage.

Sources: [39, 40, 41, 42, 43, 44, 45]

### Box 1: Aluminium–oxygen systems

Aluminium–oxygen energy systems can be seen as a related class of metal–air energy carriers (see previous topic) but used primarily for long-duration energy storage rather than rechargeable cycling.

Aluminium acts as a chemical fuel: energy is released when it reacts with oxygen or steam, producing heat, electricity, or hydrogen while forming aluminium oxide.

Because the energy is stored in the metal itself and regenerated externally, these systems are often compared to hydrogen storage in electrical terms, relying on chemical conversion rather than electrochemical recharge.

Key advantages include the global abundance of aluminium and an already mature industrial and recycling infrastructure, which could reduce scale-up barriers compared with newer energy carriers.

Some recent process designs also avoid fluorinated additives, meaning PFAS<sup>14</sup> are not inherently required, though this depends on the specific electrolyte or process configuration.

Current concepts increasingly combine aluminium energy systems with fast-response storage technologies (batteries or supercapacitors). This hybrid architecture allows aluminium to provide long-duration or seasonal energy supply, while electrochemical

<sup>13</sup> Electrocatalysis is the use of specially designed materials (electrocatalysts) on an electrode surface to speed up the electrochemical reactions that occur when a battery or other device charges and discharges.

<sup>14</sup> PFAS (per- and polyfluoroalkyl substances) are a large family of human-made chemicals often called “forever chemicals” because they break down extremely slowly in the environment. They are used for their water-, grease- and stain-repellent properties in many products (for example, coatings, textiles, packaging) and are increasingly regulated due to concerns about persistence, accumulation in ecosystems and potential health impacts.

storage handles rapid power response and cycling.

However, several challenges remain, including low round-trip efficiency, high-temperature process requirements, and the need to demonstrate large-scale material regeneration and system integration.

Sources: [46, 47]

### A.1.5 - Lithium-sulphur battery

Lithium-sulphur (Li-S) batteries are an emerging electrochemical energy storage technology that uses sulphur cathodes paired with lithium metal or lithium-based anodes. In theory, this chemistry offers substantially higher energy density than conventional lithium-ion systems.

Although laboratory and pilot-scale prototypes have demonstrated promising performance, large-scale commercial deployment remains limited. Compared with mature lithium-ion technologies, Li-S systems still face significant challenges, particularly regarding cycle life and long-term durability.

Recent developments suggest growing experimentation beyond mobility applications. Interest is increasing in configurations designed for long-duration and stationary energy storage, where constraints on volume and weight are less critical.

Researchers and developers are exploring semi-liquid and flow-like Li-S architectures (see A.1.3), often combined with advanced battery management systems and data-driven state-of-health monitoring (see B.1.1). These approaches aim to address intrinsic challenges of Li-S chemistry—including polysulphide shuttle effects<sup>15</sup>, electrode degradation, and safety concerns—while taking advantage of emerging supply chain capabilities and early industrial deployment, particularly in Asia and notably in China.

These technological and system-level advances create several potential opportunities for stationary energy storage systems, including:

- Long-duration grid storage to balance variable renewable generation in applications where space and weight constraints are secondary.

- Hybrid stationary systems that integrate Li-S modules with photovoltaics, wind generation, or backup power systems to optimise energy management and improve operational flexibility.
- Port-side and shore-based storage systems that support the electrification of maritime operations, including cold ironing<sup>16</sup> and hybrid energy hubs.
- Commercial and industrial energy storage applications requiring both rapid response and extended discharge durations.

Realising these opportunities at scale will require progress on several fronts:

- Improving cycle life and stability by mitigating key degradation mechanisms inherent to Li-S chemistry, including polysulfide shuttle reactions, electrode volume expansion, and material degradation.
- Demonstrating reliable long-term performance at the system level, including effective thermal management, robust safety strategies, and predictable operational behaviour under stationary use conditions.
- Reducing capital costs and scaling manufacturing processes beyond pilot deployments so that Li-S technologies can compete with established stationary storage solutions.
- Achieving regulatory acceptance and financial bankability. For novel architectures—such as semi-liquid, hybrid, or flow-like Li-S systems—this will depend on accumulating operational data, developing appropriate technical standards, and demonstrating safety, reliability, and performance over the full project lifetime.

Sources: [48, 49, 50, 51]

## A.2 Thermal

### A.2.1 - Carnot battery

Carnot batteries are power-to-heat-to-power systems that store electricity as high-temperature heat and later convert that heat back into electricity when needed. They are not a single standardised technology but a system concept with different configurations across multiple applications.

Their novelty lies in reframing thermal energy

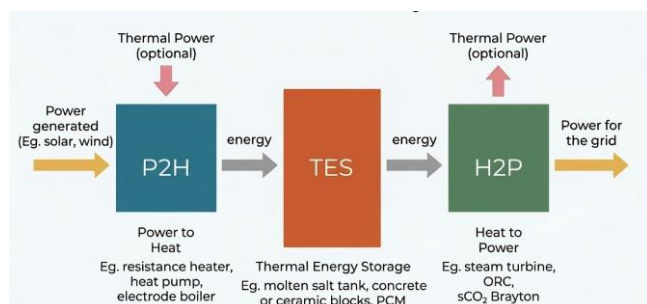
<sup>15</sup> In sulfur-based batteries, “polysulfide shuttle effects” happen when some sulfur compounds dissolve into the electrolyte and wander from one electrode to the other instead of staying where they are useful. As they move back and forth, they waste stored energy and slowly damage the battery, leading to faster capacity loss and lower efficiency.

<sup>16</sup> Cold ironing refers to supplying electricity from the shore to a ship at berth so that it can switch off its onboard generators while docked, reducing fuel use and emissions.

systems as electricity storage assets. Electricity is converted to heat using resistive heaters, heat pumps, or other approaches, stored in thermal media, and then reconverted into electricity through thermodynamic power cycles.

Recent signals point to advances in thermodynamic cycles, high-temperature heat pumps, and alternative heating techniques such as microwave heating to improve conversion pathways (though further research is needed to increase system efficiency).

**Figure 2.** Simplified scheme of a Carnot battery



Source: Authors based on the sources referenced below.

Carnot batteries create opportunities to balance variable renewable electricity by shifting surplus power into thermal storage for later power generation. Key use cases include:

- Grid-scale storage where long duration is prioritised over high round-trip efficiency.
- Coupling electricity storage with industrial or district heat supply, enabling multi-output systems that deliver both power and heat.
- Retrofitting or hybridising thermal power plants to provide additional flexibility services.
- Niche configurations where alternative heating methods, such as microwave-based solutions, better match specific storage media.

Further development will be shaped by several technical and system-level challenges:

- Low round-trip efficiency in real-world conditions, especially where high-performance heat pumps are absent.
- Dependence on high-temperature materials and components with limited operational experience.

- Unclear system and conceptual boundaries as well as terminology, complicating comparison, assessment, and system design.
- Scaling and validating alternative heating approaches, including microwave-based solutions, across different storage media.

Sources: [52, 53, 54, 55, 56, 57, 58]

## Box 2: Metal-Organic Frameworks

Metal-organic frameworks (MOFs) are crystalline porous materials made of metal ions and organic linkers, with tunable pore structures and surface chemistry. In thermal energy storage (TES), their potential lies mainly in combination with other materials, such as refrigerants or thermochemical salts, to create MOF-based sorbents or hybrid MOF-salt composites with improved energy density and system flexibility.

Potential applications include compact sorption-based<sup>17</sup> TES for buildings and district heating, solar-driven thermochemical storage using MOF-salt composites, and MOF-based structured adsorbents or coatings that enhance heat and mass transfer in adsorption heat pumps and low-temperature heating or cooling systems.

However, despite significant research activity, practical deployment remains limited. Key challenges include reducing synthesis cost and environmental impact through greener production routes, developing environmentally friendly and low-cost MOFs, ensuring long-term hydrothermal and cycling stability, and improving shaping<sup>18</sup> and reactor integration while maintaining high sorption capacity.

System-level and techno-economic assessments are also needed to identify niches where MOF-based TES can outperform conventional materials such as zeolites, silica gels, and salt hydrates.

Sources: [59, 60, 61, 62, 63]

<sup>17</sup> Sorption is a general term for the way one substance attaches to or is taken up by another, covering both adsorption (sticking to a surface) and absorption (being taken inside a material). In energy and thermal storage, sorption processes are used to hold and later release heat or gases, which can improve efficiency, stability, or safety in certain system designs.

<sup>18</sup> Shaping in this context refers to processing MOF powders into macroscopic, mechanically stable forms (such as pellets, beads, monoliths, or structured coatings) that can be packed into reactors or coated onto heat exchangers while preserving high sorption capacity and good heat and mass transfer.

## A.2.2 - Metallic phase change

Metallic phase change materials (m-PCMs) store and release heat through the solid–liquid phase transition of metals or metal-based composites. Compared with organic or salt-based PCMs, they provide higher thermal conductivity, faster thermal response, and the ability to operate at higher temperatures.

Workshop discussions highlighted two main technological approaches: using metals directly as phase change media or incorporating metals into composite structures to enhance heat transfer and improve structural performance.

Recent innovation is particularly visible in composite designs that combine metals with supporting materials such as foams, nano-additives, or organic matrices. These configurations aim to overcome heat-transfer limitations while simultaneously adding mechanical stability or multifunctional properties. Advances in metal foams, nano-encapsulation, and additive manufacturing are enabling the design of tailored material architectures, which are especially relevant for high-temperature thermal energy storage applications.

Recent developments include also the use of industrial by-products—such as steel slag—as structural carriers for phase change materials. This approach suggests potential pathways toward lower-cost, more circular, and more sustainable metallic PCM systems, particularly for applications that do not require extremely high operating temperatures.<sup>19</sup>

These technologies create opportunities across several heat-focused applications:

- High-temperature thermal energy storage for industrial waste-heat recovery and process-heat buffering.
- Solar-thermal and solar-thermal-electric systems that require rapid charging and discharging of stored heat.
- Thermal management in power electronics, batteries, and other systems experiencing high heat flux.
- Integrated energy-conversion concepts that combine thermal storage with electro-thermal or magneto-thermal inputs.

However, further development depends on overcoming several technical and system-level challenges:

- Scaling the manufacturing of metal foams, composite structures, and nano-enhanced PCMs while maintaining acceptable cost and quality.
- Managing thermal stresses, phase stability, and long-term cycling performance under high-temperature operating conditions.
- Developing reliable multiphysics models to guide material design and system integration.
- Improving material sustainability, including reducing reliance on critical raw materials and enhancing recyclability.

Sources: [64, 65, 66, 67, 68, 69]

### Box 3: Reversible chemical reaction systems

Reversible chemical reaction systems store thermal energy through sorption reactions between a solid sorbent and a vapour, typically water. Heat is stored by driving desorption at elevated temperatures and released through sorption at lower temperatures.

Because energy is stored in the chemical potential of the reaction rather than as sensible heat, these systems can achieve very low thermal losses, enabling long-duration storage compared with conventional sensible or latent heat technologies.

Key applications include:

- Seasonal heat storage for buildings, especially with low-temperature heating or cooling systems.
- Recovery and long-term reuse of industrial waste heat.
- Thermal buffering for renewable heat sources to better match supply and demand.

Key development challenges:

- Improving sorbent stability, cycling durability, and water uptake in real conditions.
- Scaling material production and reactor design while maintaining heat and mass transfer.

<sup>19</sup> Steel slag is a stony, ceramic-like by-product left over from steelmaking, produced when impurities in molten steel are separated out and solidify as lumps or gravel. Instead of being landfilled, this high-temperature-resistant material can be reused as a low-cost medium for thermal energy storage, absorbing heat when it is available and releasing it later for industrial processes or power generation.

- Integrating systems into existing thermal infrastructure at acceptable cost.
- Demonstrating long-term performance at pilot and system scale.

Sources: [70, 71, 72]

### A.3 Mechanical and hybrid

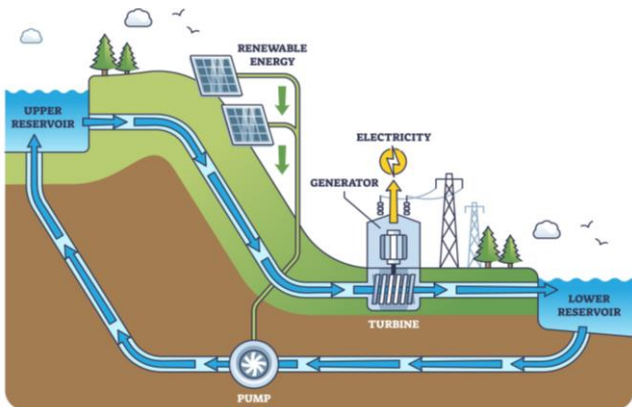
#### A.3.1 - Pumped storage hydropower

Pumped storage hydropower (PSH) is a mature, large-scale energy storage technology that stores electricity by moving water between reservoirs at different elevations. When electricity supply exceeds demand, water is pumped to a higher reservoir. When electricity is needed, the water is released through turbines to generate power. Because it can store large amounts of energy and discharge over many hours, PSH plays a key role in balancing power systems with high shares of variable renewable generation such as wind and solar.

In the EU, it remains one of the main reference technologies for long-duration energy storage, although new projects typically face long planning and construction timelines.

Recent developments focus on improving the performance and flexibility of existing systems. One area of innovation involves the use of denser-than-water working fluids, which can increase the amount of energy stored per unit of reservoir volume.

Figure 3. Scheme of pumped storage hydropower



Source: Adobe Stock (stock.adobe.com)

At the same time, digital enabling technologies are being applied to existing plants through advanced control systems, real-time monitoring, and turbine optimisation, allowing operators to improve

efficiency and responsiveness.

There is also growing interest in hybrid configurations that combine pumped storage with battery systems, enabling operators to address different balancing timescales within a single integrated setup.

These developments create several concrete opportunities for power system operation:

- Mid- to long-duration balancing to manage extended periods of variability in renewable generation.
- Hybrid operation with batteries, where batteries provide rapid, short-duration balancing and pumped storage supplies sustained energy delivery.
- Reduced mechanical stress on hydro turbines by shifting rapid start-stop and high-frequency balancing services to battery systems.
- Expanded deployment potential through higher-density fluids and the upgrading or repurposing of existing reservoirs.

However, several challenges and development needs remain:

- Long lead times for new facilities, requiring early strategic planning and complex permitting processes.
- Limited availability of suitable sites for new reservoirs, increasing reliance on retrofitting existing infrastructure and hybrid configurations.
- High upfront capital costs and substantial civil engineering requirements.
- Coordinated system design to optimise how battery systems and pumped storage assets operate together within the power system.

Sources: [73, 74, 75, 76]

#### A.3.2 - Battolyser architecture

The battolyser is a hybrid energy storage technology that combines a rechargeable battery with an electrolyser<sup>20</sup> within a single device. In practice, it functions as a battery at lower charge levels, storing electricity electrochemically. Once the battery becomes fully charged, the system automatically shifts to hydrogen production through electrolysis. This allows the device to provide both short-term electricity storage and longer-duration energy

<sup>20</sup> An electrolyser is a device that uses electricity to split water into hydrogen and oxygen. The hydrogen produced can then be stored and used later as an energy carrier or industrial feedstock.

storage in the form of hydrogen.

Recent development efforts focus on system designs that enable a smooth transition between battery operation and electrolysis. Researchers are also adapting and optimising mature battery chemistries, such as nickel–iron and lead–acid, for integrated battery–electrolyser systems, partly due to their lower reliance on CRMs and other scarce materials.

Several potential applications are emerging:

- Grid balancing in renewable-heavy power systems, where the device can provide rapid electrical storage while also producing hydrogen during periods of excess electricity generation.
- Seasonal energy storage through on-site hydrogen production when surplus renewable electricity is available.
- Decentralised or off-grid energy systems that require both short-term power reliability and longer-term energy autonomy.
- Integration of renewable electricity with hydrogen supply for industrial processes or mobility applications.

Several technical and economic challenges remain:

- Uncertain scalability and system optimisation, particularly when using less conventional battery chemistries.
- Gaps between theoretical performance and observed efficiency, especially in early designs based on lead–acid batteries.
- Complex system integration requirements, as control strategies must manage both battery cycling and electrolysis within the same device.
- Robust techno-economic and lifecycle assessments to determine whether battery systems can compete with systems that use separate batteries and electrolysers.

Sources: [77, 78, 79, 80, 81, 82]

### A.3.3 -Thermophotovoltaic heat battery

Thermophotovoltaic heat batteries store electrical energy as high-temperature heat and then either convert it back into electricity or supply it directly as usable heat. They are designed for long-duration storage, especially for industrial demand, by decoupling energy storage capacity from power output and using thermal instead of electrochemical processes.

Recent developments focus on systems that use

solid carbon blocks as the storage medium, combined with thermophotovoltaic converters that generate electricity from radiant heat.

Workshop participants emphasized the use of earth-abundant, low-cost materials and the ability to operate at very high temperatures as key advantages over conventional battery storage.

These systems create several concrete opportunities:

- Long-duration energy storage to support grid stability during extended periods of low renewable generation.
- Direct provision of high-temperature heat for industrial processes that are hard to electrify.
- On-site conversion between electricity and heat, increasing flexibility in industrial energy management.
- Reduction of fossil fuel use in heat-intensive industrial sectors.

However, several challenges and development needs remain:

- Efficiency losses when converting stored heat back into electricity.
- Ensuring materials durability and effective thermal management at sustained high operating temperatures.
- Technical and operational integration with existing industrial facilities and grid infrastructure.
- Large-scale demonstration projects to prove cost-effectiveness, performance, and reliability over time.

Sources: [83, 84, 85, 86]

## B. Enabling technologies

### B.1 Enabling technologies for electrochemical energy storage

#### B.1.1 – Developments in IT

Advances in digital tools—particularly artificial intelligence (including generative models) and computational chemistry—are increasingly supporting the discovery and optimisation of materials and processes for energy storage.

Recent signals point to the growing use of multiscale modelling approaches that combine atomistic simulations, computational chemistry and physical experimentation. Together, these methods provide deeper insight into reaction pathways and material behaviour across different scales.

Workshop discussions highlighted the increasing convergence between AI-driven modelling and experimental characterisation.

However, further progress will depend on several factors: the availability of reliable and well-curated datasets, stronger integration between modelling and laboratory validation, and the ability to translate modelling insights into scalable materials and industrial processes.

Sources: [87, 88, 89, 90, 91, 92]

#### Box 4: Computational chemistry modelling

As already mentioned in the previous topic on IT developments (B.1.1), computational chemistry modelling is increasingly used to identify new materials and optimise existing ones for energy storage applications.

By combining physics-based simulations with artificial intelligence and machine-learning techniques, researchers can predict molecular structures, reaction pathways, and material properties, accelerating the discovery and optimisation of electrode, electrolyte, and redox materials while reducing the need for extensive experimental testing.

#### B.1.2 – CRM-free and recyclable membranes

Research on CRM-free and recyclable membranes and electrolytes is emerging as a promising pathway towards more sustainable flow battery systems. Recent signals and the workshop discussions point to growing efforts to design membrane materials and electrolyte chemistries using abundant or recyclable substances, while still maintaining key performance characteristics such as ionic conductivity, selectivity and chemical stability.

In flow batteries, membranes and electrolytes play a critical role. They regulate ion transport and prevent cross-contamination between the electrolyte tanks, which directly affects system efficiency, durability and operational safety. As a result, the materials used in these components are central to overall battery performance.

Developing alternatives that reduce reliance on CRMs could strengthen supply-chain resilience and improve lifecycle sustainability. However, many of the proposed materials and chemistries are still at an early stage of research. Further research and innovation across multiple technology readiness levels (TRLs) will be required to demonstrate

long-term stability, scalable manufacturing processes and economic viability.

Sources: [93, 94]

#### B.1.3 – Coupling hydrogen to anode-side chemistry

During the workshop discussions, participants raised the possibility of integrating hydrogen production and storage with the anode-side chemistry of electrochemical systems that combine elements of hydrogen storage and redox flow battery concepts.

In such configurations, the anode remains a solid electron-conducting electrode, while redox-active species in the anolyte can mediate water splitting in external catalytic reactors to generate hydrogen as an energy carrier.

This approach aligns with redox dual-flow or dual-circuit battery concepts, where a primary electrochemical storage function is complemented by a secondary hydrogen platform in which charged electrolytes are chemically discharged to produce and store hydrogen fuel.

These hybrid architectures offer a potential bridge between large-scale redox-flow electricity storage and hydrogen infrastructure, enabling flexible allocation of surplus renewable electricity either to electrochemical storage or to hydrogen production and subsequent use in fuel cells or other hydrogen technologies.

Sources: [95, 96]

#### B.1.4 – Particle, layer and process engineering for advanced electrodes

Workshop discussions highlighted particle, layer and process engineering as closely linked levers for improving battery performance and manufacturability.

Participants emphasised the role of thin-layer deposition in solid-state batteries, where precise control over the thickness, composition and placement of interfacial layers can strongly influence ion transport, interfacial stability and overall device performance.

At the materials level, particle engineering, such as tailoring particle shape, grain size and porosity, was identified as important both for cathode active materials and for electrode preparation more broadly, because these features govern electrochemical behaviour, mechanical integrity and long-term durability.

Participants also pointed to low-cost electrode

manufacturing approaches that could replace solvent-intensive slurry<sup>21</sup> processing with water-based or dry methods, linking microstructural control to scalable production.

Water-based processing substitutes toxic organic solvents with aqueous binders while maintaining comparable electrochemical performance, thereby reducing health, safety and environmental burdens in manufacturing.

Dry electrode processes go further by eliminating solvents entirely, offering potential reductions in energy use, equipment and dry-room requirements, and overall production costs, while still enabling controlled particle packing and interfacial architectures in both conventional and solid-state battery designs.

Sources: [97, 98, 99]

### B.1.5 – Electrode, electrolyte, and interface materials

Advances in electrode, electrolyte and interface materials are key enablers for improving the performance, durability and safety of electrochemical batteries designed for mid- to long-term energy storage.

Progress in areas such as stable electrode chemistries, high-conductivity electrolytes and engineered interfaces can improve ion transport, limit degradation over extended cycling periods and support the deployment of larger-scale stationary battery systems.

Sources: [100, 101]

### B.1.6 – Low-cost anodes for sodium-ion batteries

Low-cost hard carbon and related materials for sodium-ion (Na-ion) battery anodes are being explored to improve the scalability and economic viability of Na-ion systems for stationary and mid- to long-duration energy storage.

Candidate materials based on abundant carbon sources (for example biomass- or coal-derived precursors) or engineered carbon structures aim to deliver sodium storage capacities comparable to state-of-the-art hard carbon anodes, while lowering precursor and processing costs and enabling more scalable and simplified manufacturing.

Sources: [102, 103, 104]

### B.1.7 – Carbon nanotubes for cathodes

Distinct from the development of low-cost carbon anodes, carbon nanotubes are being explored as conductive additives in cathodes such as lithium iron phosphate (LFP) and nickel–manganese–cobalt (NMC) oxide systems, as well as in sulphur-based batteries, where small concentrations can significantly improve electronic conductivity.

By forming efficient conductive networks within the electrode, they can enhance charge transport, enable higher active-material utilisation and support the performance of electrochemical batteries including those targeted for stationary mid- to long-term energy storage applications.

Sources: [105, 106]

### B.1.8 – Solid redox mediators

Solid redox mediators are emerging materials that facilitate electron transfer between electrodes and reactants in electrochemical systems, improving reaction kinetics and reducing overpotentials<sup>22</sup> in advanced battery chemistries.

Signals highlight their potential role in metal–CO<sub>2</sub> batteries, where they act as intermediaries that enable more efficient electrochemical conversion of CO<sub>2</sub> and help address the slow reaction rates that currently limit these systems.

By improving charge-transfer processes, solid redox mediators could enhance efficiency, stability and cycle life in batteries that combine energy storage with CO<sub>2</sub> utilisation.

However, these approaches remain at an early research stage, with key uncertainties relating to reaction mechanisms, material durability and the development of cost-effective mediator and catalyst systems suitable for scalable energy storage applications.

Sources: [107]

## B.2 Enabling technologies for thermal energy storage

### B.2.1 – Compact heat exchange units

Compact heat exchange units are emerging as an enabling component in high-temperature thermal energy storage systems, particularly those using

<sup>21</sup> In this context, a “slurry” is a thick liquid mixture of battery materials (active material, binder and additives) dispersed in a solvent and coated onto a metal foil to form the electrode layer.

<sup>22</sup> In this context, “overpotentials” are the extra voltage losses that occur because real electrochemical reactions are not perfectly efficient, so the battery needs more voltage to drive the reaction than theory would suggest, and some of that energy is dissipated as heat instead of being stored.

molten or fused salts as storage media.

Signals highlight designs that maximise the heat-transfer surface area between hot storage fluids and working fluids. This enables faster and more controlled thermal exchange during charging and discharging cycles. Improved heat transfer can enhance system efficiency, responsiveness and operational stability in applications such as concentrated solar power or Carnot battery systems (see A.2.1).

However, workshop discussions emphasised that scaling these units to large industrial systems remains challenging. Compact geometries must withstand high temperatures, corrosion from molten salts<sup>23</sup> and mechanical stresses, while still providing reliable performance and cost-effective manufacturing at larger scales.

Sources: [108, 109]

### B.2.2 – Microwave heating system

A microwave heating system is an electromagnetic heating method that uses microwaves to directly heat materials with dielectric properties. Unlike conventional resistive heating, microwave heating provides volumetric and selective heating. This can lead to more efficient and uniform temperature distribution.

In one of the signals collected, the microwave heating system is used to heat solar salt<sup>24</sup>, addressing the limitations of traditional electric heating methods. This enables the Carnot battery (see A.2.1) to operate at higher temperatures with reduced degradation. As a result, it improves the overall performance and longevity of the thermal energy storage system.

Sources: [52]

### B.2.3 – Plasma heating

Plasma heating is a method of generating high temperatures by ionising a gas into a plasma state, which is then used to transfer heat to a target material or process. This technology uses electrical energy to create and sustain a plasma arc, providing intense and highly controllable heating. In the context of one collected signal, plasma heating is integrated into chemical processes to enable

high-temperature reactions driven by renewable electricity.

This advanced heating approach can reduce carbon emissions (when powered by low-carbon electricity) and improve process controllability and dynamics by providing precise and rapid heating, which is crucial for optimising certain chemical reactions and system operation.

Sources: [110, 111, 112]

### B.2.4 – Underground thermal reservoir

Underground thermal reservoirs are being explored as enabling infrastructure for large-scale thermal energy storage. They use subsurface formations such as aquifers or borehole systems to store heat or cold in geological materials or groundwater.

Signals highlight their role in applications such as reservoir thermal energy storage for data-centre cooling. In these systems, cold energy<sup>25</sup> generated during off-peak periods can be stored underground and released when demand increases, reducing peak electricity consumption.

Workshop discussions noted that similar subsurface storage concepts are already used in other energy systems, including compressed air energy storage and potentially CO<sub>2</sub>-based cycles.

Their main advantage is the ability to store large thermal volumes with relatively little surface infrastructure. However, performance depends strongly on local geological conditions and careful system design to ensure efficient heat transfer and long-term operational stability.

Sources: [113, 114]

## B.3 Enabling technologies for mechanical and hybrid energy storage

### B.3.1 – Thermal integration system

Thermal integration systems capture, and reuse waste heat generated during energy conversion and storage processes, improving overall system efficiency.

In high-temperature electrochemical technologies such as protonic ceramic electrochemical cells, this waste heat can, in principle, be recovered and reused

<sup>23</sup> Salts heated above their melting point so they become a liquid and can conduct ions. In high-temperature batteries and thermal-storage systems, these liquid salts act as the medium that stores and transfers energy, taking advantage of their stability at several hundred degrees Celsius.

<sup>24</sup> Solar salt refers to the widely used molten nitrate mixture of roughly 60% NaNO<sub>3</sub> and 40% KNO<sub>3</sub>, which serves as a standard heat-transfer and storage medium in high-temperature thermal energy storage systems.

<sup>25</sup> In these systems, cooling capacity generated during off-peak periods can be stored underground as low-temperature thermal energy and released when demand increases, reducing peak electricity consumption.

within the system or in downstream processes.

Although the core storage mechanism is electrochemical, the ability to capture and reuse high-temperature waste heat gives these systems a hybrid character.

This hybrid integration can raise overall efficiency and broaden the range of useful services, for example co-producing electricity, hydrogen, and process heat.

Sources: [115, 116, 117]

### B.3.2 – Hydraulic short-circuit operation

Hydraulic short-circuit operation is an emerging operating mode in pumped-storage hydropower (PSH) that allows simultaneous pumping and generation within the same hydraulic circuit, increasing operational flexibility (see A.3.1).

Signals indicate that advances in electro-mechanical equipment and variable-speed machines enable PSH plants to operate across a broader range of flow and power levels rather than at a single pumping set-point.

Workshop discussions highlighted that this could improve the ability of PSH to adjust pumping loads in response to fluctuating grid conditions, supporting therefore the integration of renewables. However, implementing such operation introduces additional complexity in turbine-pump control, hydraulic stability and system optimisation, requiring further engineering development and operational testing.

Sources: [118, 119]

### B.3.3 – Multi-microgrid energy storage system

Multi-microgrid energy storage systems are emerging as an enabling architecture that allows multiple interconnected microgrids to coordinate and share storage resources, rather than deploying isolated systems.

Signals highlight approaches that optimise capacity allocation and scheduling across distributed storage assets using advanced optimisation algorithms and game-theoretic coordination models.

By pooling storage capacity, these systems can improve the integration and use of variable renewables such as wind and solar. They also support load balancing and frequency stability, and can underpin multi-carrier energy systems that deliver electricity, heat or hydrogen.

Signals also emphasise the potential for improved asset utilisation and cost efficiency, but note challenges related to coordination among

stakeholders, operational complexity and the need for robust digital control and market arrangements.

Sources: [120, 121]

Figure 4 – Worker with a digital dashboard



Source: Adobe Stock (stock.adobe.com)

### Box 5: Digital twins

Digital twins are virtual replicas of physical systems that combine real-time operational data with simulation models to monitor, analyse, and optimise performance. In pumped storage hydropower systems (see A.3.1) for example, digital twins can support predictive maintenance and operational optimisation by anticipating stress on components such as turbines and pumps, which are increasingly exposed to frequent start-stop cycles as plants provide short-term grid balancing services. Sources: [122]

### B.3.4 – Second-life batteries

Second-life batteries are already being used as an enabling component in hybrid energy storage strategies. Repurposed batteries are combined with other storage technologies to provide complementary services.

Workshop discussions highlighted their potential integration into systems such as pumped-storage hydropower (see A.3.1), where batteries can deliver fast-response, short-duration services including frequency regulation and peak balancing, while hydropower reservoirs provide longer-duration energy storage.

This hybrid configuration can improve overall system flexibility and reduce operational stress on mechanical components such as turbines by smoothing rapid power fluctuations.

Sources: [123, 124]

## Contextual factors

The following contextual factors shape the development and uptake of mid- to long-duration energy storage technologies and innovations. They stem from an aggregation of participants' insights<sup>26</sup>, re-organised using the STEEP<sup>27</sup> framework.

### Social

#### Public awareness and acceptance

Participants suggested that societal awareness of the role of energy storage in enabling renewables and grid resilience, will influence technology uptake and support for new projects.

Rising public concerns about safety, environmental impacts, large projects (e.g. dams for pumped storage), and the visibility of outages or extreme-weather events may further shape acceptance and project timelines

#### Safety perceptions

Safety considerations, particularly for battery systems used in second-life applications, and stationary storage, were raised.

Ensuring safe technologies, robust maintenance practices, and clear communication about risks may facilitate adoption, while incidents or perceived risks could undermine public trust and trigger stricter regulation.

### Technological

#### Flexibility, multi-purpose functionality, and convergence

Experts highlighted advantages of technologies capable of serving multiple purposes, such as delivering various grid services, supporting technology convergence, and storing different energy carriers.

Recognising the multi-purpose value of storage (e.g. pumped storage hydropower storing both energy and water, power-to-heat combined with thermal storage) was seen as important for decarbonisation and grid flexibility, but designing systems that meet

multiple requirements increases technical complexity.

#### Manufacturability, scale-up, and infrastructure readiness

Several participants stressed that new battery chemistries and storage technologies are more likely to scale if they can be manufactured on existing production lines.

Conversely, technologies that depend on completely new manufacturing infrastructure or large expansions of grid and storage assets were seen as carrying higher investment risks and likely experiencing slower uptake. For such options, upscaling and the potential to expand across Europe should therefore be prioritised.

#### Technology performance, duration, and system integration

The ability to deploy solutions across diverse European climatic zones and to deliver different storage durations (e.g. 8–72 hours, multi-day and seasonal storage) was seen as critical for network resilience in low-sun/low-wind situations.

Participants underlined the importance of system thinking, including grid integration, hybridisation, and service stacking, so that solutions can link power, heat, transport, and industry and be useful for multiple applications.

#### Digitalisation, cybersecurity, and research infrastructure

Digital twins, smart grids, and predictive maintenance systems were seen as tools to optimise operation and accelerate innovation, especially when supported by well-resourced research infrastructures (e.g. for materials research and device development).

However, increasing digitalisation may introduce new vulnerabilities, making cybersecurity a growing concern for storage assets and smart grids.

#### Technology competition and lock-in

The future role of storage may depend on developments in alternative technologies such as geothermal energy or other renewables, which could reduce the need for some storage applications.

At the same time, the current dominance of specific

<sup>26</sup> These factors were analysed initially using an adapted version of the "Triangle of the Future" framework [127], a foresight method that maps three competing forces: the pull of the future, the push of the present, and the weight of history. It can be used as a stand-alone method or in conjunction with others. For this project, the authors explored 3 types of contextual factors connected with those three temporal dimensions: drivers which are high-level factors that trigger or shape significant contextual changes and pull technological development and uptake into the future; enablers, or opportunities, that are present-day conditions that create a fertile ground for innovation to occur and therefore push technologies forward; and barriers, or challenges, that can be seen as past and present constraints ("weight") that hinder technological development and uptake.

<sup>27</sup> STEEP - Social, Technological, Economic, Environmental and Political/Policy factors.

chemistries (e.g. lithium iron phosphate in stationary energy storage systems) and existing market confidence in them, may create lock-in effects and make it harder for alternative concepts to reach scale.

## Economic

### Cost trajectories and market dynamics

The cost of energy storage technologies, including capital expenditure (CAPEX) and operational expenditure (OPEX) such as maintenance, remains central to deployment decisions.

Large-scale production of electric vehicles cells has helped drive down costs for energy storage systems. But cost trajectories differ by technology and low upfront cost does not necessarily imply low end-of-life or recycling costs.

### Revenue streams, service stacking, and market access

Storage technologies may benefit from the ability to provide multiple grid services and revenue streams, but participants noted that current electricity market structures and access rules do not always reward the flexibility that storage provides.

Access to grid services markets and the need to improve the harmonisation across Member States were highlighted as barriers for some actors.

### Investment risks, infrastructure, and funding strategies

Although financial instruments exist at EU and national level, policy and market uncertainty, together with long and complex permitting procedures, increase investment risk perception, especially for capital-intensive, long-duration assets.

A major obstacle for some technologies is the need for entirely new infrastructure or processes. Several participants noted both the tendency to spread funds across many options and the funding calls that try to tackle many challenges at once, which can delay short-term initiatives.

### Industrial value chains, autonomy, and supply chains

Strengthening European industrial capabilities, building local supply chains, and aligning technologies with EU manufacturing strengths were seen as key to value creation and technological autonomy.

At the same time, global production structures, dependence on CRM, the dominance of non-EU processing for some materials, and other

supply-chain vulnerabilities were viewed as significant challenges.

## Environmental

### Decarbonisation, electrification, and resilience

Electrification of heating and broader decarbonisation trends are expected to increase demand for thermal and long-duration storage, including seasonal solutions.

Participants also linked storage needs to more frequent extreme-weather events and related outages, underlining the role of resilient and decentralised systems.

### Environmental impacts of infrastructure

Large-scale storage infrastructure such as pumped hydropower may raise concerns about ecosystem impacts and land or water use, which partly explains why such options are sometimes overlooked despite relatively low lifecycle greenhouse-gas emissions per unit of energy stored.

New concepts, including using existing or abandoned mines for pumped storage were mentioned as ways to reduce impacts and shorten timelines.

### Circularity, recycling, and end-of-life

End-of-life management, recycling, ecodesign, and bio-based or “bio storage” concepts were seen as increasingly important for future storage systems.

Experts noted that recycling economics depend strongly on material value: low-metal-value batteries require low-cost recycling processes and/or support from policy initiatives, while technologies using high-value materials can be designed with a full-cycle recovery in mind.

Figure 5. Wind turbines and solar panels farm in a field.



Source: Adobe Stock (stock.adobe.com)

## Materials choices, benign resources, and regulation

Technologies that use benign, abundant, or locally available materials were seen as offering environmental and resilience benefits, provided their large-scale impacts are carefully assessed.

Regulatory developments, such as restrictions on certain substances (e.g. PFAS in membranes and separators), were also highlighted as factors shaping technology choices.

## Policy

### Policy coherence and strategic prioritisation

Participants noted that the EU policy landscape for energy storage may be fragmented, with numerous initiatives and extensive legislation distributed across technologies and levels of governance.

While this diversity can support experimentation, it may dilute strategic focus if clear priorities are not established regarding which technologies and value chains should be supported across the full lifecycle.

### Regulatory frameworks, permitting, and market design

Lengthy permitting processes for underground storage, pumped hydropower (including modernisation of existing sites), and other infrastructure were identified as key bottlenecks.

Experts also noted that current energy market design and grid regulation do not always reward the types of storage solutions needed in future energy systems. They added that grid upgrades are progressing too slowly to fully benefit from new storage capacity and the growing share of renewables.

### Strategic resilience, geopolitics, and competing priorities

Geopolitical developments, supply-chain risk, and the desire for energy and technological autonomy were recurring themes, with storage seen as a contributor to resilience and reduced import dependence.

Some participants also pointed to the fact, that competing political priorities (e.g. defence) may divert attention and funding away from energy-storage.

### Coordination and governance across actors and projects

Energy production, grid operation, and storage often involve different actors and regulatory frameworks, making it difficult to develop integrated business models.

Better coordination between stakeholders, EU projects, tools, and policy initiatives—breaking silos and improving information sharing—was seen as necessary to accelerate technological development and deployment.

## Conclusions

The previous sections summarised the main outcomes and priority areas for each storage “family”. This concluding section highlights a smaller set of cross-cutting insights that recur across the exercise and become clearer when technology and context are viewed together.

A first recurrent point is that the future of mid- to long-duration energy storage is unlikely to be shaped by one dominant technology. The landscape appears to be moving towards a portfolio logic, in which different storage solutions serve different durations, services and system contexts.

Electrochemical, thermal, mechanical and hybrid systems are not simply competing substitutes. In many cases, they are complementary options responding to different needs across the power system, industry, heating and decentralised applications.

A second recurrent theme is that deployment will depend as much on system and policy conditions as on technical progress. Across the sections, similar bottlenecks reappear: permitting, market design, manufacturability, access to infrastructure, supply chains, sustainability and end-of-life strategies.

This suggests that the main challenge is not only to improve performance, but also to create conditions in which diverse technologies can scale, interact and find viable roles.

A third high-level insight is the growing importance of technology convergence. This appears in two ways:

- First, hybridisation is becoming a structural trend in itself, for example through combinations of pumped storage and batteries, battolysers linking battery storage with hydrogen production, or aluminium-based systems coupled with fast-response storage.
- Second, enabling technologies are becoming more decisive. Advances in digital tools, interface engineering, advanced manufacturing and systems integration increasingly shape what core storage technologies can achieve.

This echoes Humphry Davy’s observation, cited at

the beginning of the report, that innovation in energy storage will emerge not only from advances within the field itself, but also from its interaction with developments in materials science, digitalisation, thermal management, advanced manufacturing, and systems integration. This reinforces the role of storage technologies as both catalysts for and beneficiaries of broader technological development.

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The information and views presented here are those of the authors and do not necessarily reflect the official opinion of the European Commission.

The findings of this exercise resulted from a participatory process involving a group of internal and external experts representing a diversity of fields and backgrounds. The methodologies applied have limitations and the results do not aim to cover all developments and topics on the field.

Most trends and signals are referenced to the sources where they were originally detected, although some concepts included in the final texts result from the analysis and contributions of the participants and the authors.

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