TECHNOLOGY ROADMAP FOR HYBRIDISATION OF ENERGY STORAGE

Technological pathways for the integration of multi-technology storage systems to support Europe’s clean energy transition

JUNE 2025

StoRIES

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Editorial

The StoRIES Technology Roadmap Editors and Authors Group

Editors: Roberto Scipioni (SINTEF), María Elisa Gil Bardají (KIT), and Stefano Passerini (KIT)

Authors: Roberto Scipioni (SINTEF), M. Esther Rojas Bravo (CIEMAT), Kai Heussen (DTU), Maria Mazuera (EASE), Francis Kinyanjui (SINTEF), Koruosh Malek (FZJ), Poul Norby (DTU), Manuel Baumann (KIT), Marcos Blanco (CIEMAT), Jorge Nájera (CIEMAT), Marcos Lafoz (CIEMAT), Martin Bracken (EASE), Jacopo Tosoni (EASE), Pınar Arpaçay (KIT), Ralf Peter (FZJ), Marco Ferraro (CNR), Atle Harby (SINTEF), Fride Vullum-Bruer (SINTEF), Edel Sheridan (SINTEF), Margherita Moreno (ENEA), Spyridon Pantelis (EERA), Linda Barelli (UNIPG), María Elisa Gil Bardají (KIT), and Stefano Passerini (KIT)

Reviewed by the Working Groups:

WG1: Roadmap, SRIA and materials intelligence platform - Chair: María Elisa Gil Bardají (KIT)
WG4: Technical and non-technical barriers - Chair: Maria Mazuera (EASE)

Reviewers: Aitor Ollacarizqueta (CENER), Andrea Balducci (UNIJENA), Rafael Mayo-García (CIEMAT), Enrique Luque Aleman (VOITH), Faisal Bouchotrouch (CENER), George Karagiannakis (CERTH), Vito Di Noto (UNIPD), Giovanna Cavazzini (UNIPD), Helena Navarro (UNIBIRG), Jordi Jacas Biendicho (IREC), Joris Koornneef (TNO), Leire Zubizarrtea (ITE), Lluis Trilla (IREC), Magdalena Graczyk-Zajac (EnBW), Magnus Millingen (TEXEL), Mehdi Zadeh (NTNU), Nasir Mahmood (RMIT), Paillard Elie-Elisee Georges (POLIMI), Philippe Stevens (EDF), Rafa Iturbe (ANTECSA), Remco Groenenberg (TNO), Sandra Rabaça (IST/C2TN), Sergio Persoglia (OGS), Xavier Granados (CSIC-ICMAB).

ACKNOWLEDGEMENTS

The Technology Roadmap for Hybridisation of Energy Storage has been jointly developed by experts from the Storage Research Infrastructure Eco-System (StoRIES, Grant Agreement Number 101036910), the EERA Joint Programme on Energy Storage, and the European Association for Storage of Energy (EASE). Their contributions were central to shaping the content, structure, and ambition of this document.

We gratefully acknowledge the efforts of the many researchers, industry experts, and institutional stakeholders who contributed to the development of this Technology Roadmap. Their insights and collaboration were instrumental in analysing the current landscape, identifying key hybridisation strategies, and outlining future directions for energy storage across Europe.

The StoRIES project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No 101036910

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SUMMARY

The urgent challenge of climate change necessitates a comprehensive shift towards a low-carbon economy. Central to this transformation is the evolution of the energy sector, particularly in how energy is generated, stored, and consumed. Energy storage systems (ESS) play a crucial role in enhancing the efficiency and reliability of energy systems, particularly with the increasing integration of variable renewable energy sources such as photovoltaics, concentrated solar power, as well as wind energy.

Given the intermittency and unpredictability of these renewable sources, traditional single-technology storage solutions are often insufficient. Hybrid Energy Storage Systems (HESSs), which combine different storage technologies, offer a promising path forward by combining the complementary strengths of various systems.

While this roadmap does not prescribe a specific technology development pathway, it **does provide essential input for the Strategic Research and Innovation Agenda (SRIA)** by identifying **current technology benchmarks, key performance indicators (KPIs) and existing barriers and challenges.** These challenges are examined from **technical, socio-economic, and legislative perspectives**, offering a comprehensive foundation for future R&D prioritization..

The roadmap outlines:

- The role and value proposition of HESS in future energy systems.
- Hybrid combinations of storage technologies and their potential.
- Current technology status and benchmarking.
- KPIs and targets for performance and integration.
- Technical, economic, regulatory, and social barriers to deployment.

By doing so, the document supports the **identification of future strategic research areas**, guiding European efforts toward effective, scalable, and sustainable energy storage innovations.

METHODOLOGY AND OVERVIEW

This roadmap has been developed within the framework of the **StoRIES project** (Storage Research Infrastructure Eco-System), through the collaborative efforts of researchers, industry representatives, and institutional stakeholders across Europe. The preparation of the document was coordinated by **Work Package 3** – *"Enabling breakthrough research and innovation across the whole value chain"*, which ensured consistent progress through monthly meetings held from 2022 to 2025. The draft versions of the roadmap were also presented and discussed biannually during the StoRIES Consortium meetings, allowing for continuous feedback and refinement.

The **Benchmarking and Key Performance Indicators (KPIs)** section was developed with the active support of **Work Package 4** – *"Supporting the transition towards a climate-neutral continent"*. In addition, valuable input was gathered during two dedicated workshops:

- *StoRIES – FLORES – EERA JP ES Workshop "Applications for Hybrid Energy Storage",* held on **March 23, 2023**, at **KIT, Karlsruhe, Germany**
- *Interactive Workshop: Building a common base for sustainability assessment of hybrid energy storage systems*, held on **December 6, 2023**, at the **Austrian Institute of Technology, Vienna**

The **Case Studies section (Section 4.1)** draws upon extensive contributions from experts who co-authored a collection of 17 case studies published in the forthcoming book *Hybrid Energy Storage: Case Studies for the Energy Transition*[1]. An additional case study was developed during the **Second StoRIES Summer School 2024**, titled *"Hybrid energy storage and application-oriented solutions in EU"*, held from **June 3–6, 2024**, in **Rome, Italy**. This contribution, prepared by the top-performing student working group, has been submitted for scientific publication[2].

The roadmap was finally reviewed and revised annually by dedicated working groups within the StoRIES consortium:

- **WG1: Roadmap, SRIA and Materials Intelligence Platform**
- **WG4: Technical and Non-Technical Barriers**

Through this collaborative, multi-year, and multi-stakeholder process, the roadmap presents a robust and comprehensive analysis to guide future R&I in hybrid energy storage across Europe.

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[1] Scipioni R., Gil Bardají M.E., Barelli L., Baumann M., Passerini S., (Eds.) (2025). *Hybrid Energy Storage: Case studies for the energy transition* [in press]. Springer.

[2] Ahmadi N., Das S., Delawary A., Mataloni S., Richter L., Salmelin M., Santa Maria J., Smith J., Passerini S., Scipioni R., (2025). *Decarbonizing Hard-to-Abate Sectors: a Hybrid Electrification approach for Low-Carbon Cement Production.* Manuscript submitted for publication.

LIST OF ACRONYMS

AI	Artificial intelligence	**LTES**	Large thermal energy storage
AORFB	Aqueous Organic Redox Flox Battery	**MABs**	Metal air batteries
ATES	Aquifers thermal energy storage	**MES**	Mechanical Energy Storage
BESS	Battery Energy Storage System	**NIBs**	Sodium-ion Batteries
BRP	Balance Responsible Party	**OCC**	Overnight cost of capital
BTES	Boreholes thermal energy storage	**OPEX**	Operational expenditures
BTM	Behind The Meter	**PCM**	Phase change material
CAES	Compressed air energy storage	**PEDOT**	Poly(3,4-ethylenedioxythiophene)
CAPEX	Capital expenditure	**PHES**	Pumped heat energy storage
CES	Chemical Energy Storage	**PSH**	Pumped storage hydropower
ColdC	Cold chain	**PV**	Photovoltaics
CRM	Critical raw material	**RADP**	Required average discharge price
CSTP	Concentrated solar thermal power	**RAOP**	Required average operational profit
CST	Concentrated solar thermal	**RAPS**	Required average price spread
CTES	Caverns thermal energy storage	**REEs**	Rare earth elements
DG	Distribution generation	**RES**	Renewable Energy System
DistHC	District Heating and Cooling	**RFBs**	Redox flow batteries
EES	Electrochemical Energy Storage	**SET-Plan**	Strategic Energy Technology Plan
FRC	Frequency containment reserve	**SHS**	Sensible Heat Storage
FTM	Front of The Meter	**SLB**	Second Life Batteries
FTM	Front-of-the-meter systems	**SMES**	Superconducting magnetics energy storage
GFM	Grid forming converters	**TCM**	Thermo-Chemical Material
GFW	Grid following converters	**TCO**	Total Cost Ownership
HTF	Heat transfer fluid	**TCS**	Thermo-Chemical heat Storage
IRENA	International Renewable Energy Agency	**TES**	Thermal Energy Storage
ISO	International Standard Organization	**TSOs**	Transmission System Operators
KPI	Key Performance Indicator	**UPS**	Uninterruptable Power Supply
LAES	Liquid air energy storage	**UTES**	Underground Thermal Energy Storage
LCA	Life Cycle Assessment	**VRE**	Variable Renewable Energy
LCOE	Levelized cost of electricity	**VSC**	Voltage Source Converters
LCOS	Levelized cost of storage	**WTTES**	Water Tank Thermal Energy Storage
LIBs	Lithium-ion batteries		

1. Background and motivation

The European Union is undergoing a profound transformation in its energy landscape, driven by the need to achieve decarbonization, improve energy security, and enhance grid resilience. EU's "Fit for 55" package, part of the European Green Deal, aims to reduce net greenhouse gas emissions by at least 55% by 2030, setting the stage for the EU's zero-pollution ambition and acting as a stepping-stone to achieving the 2050 climate neutrality goal (European Commission, 2021). The transition to a low-carbon economy is imperative in the fight against climate change. Energy production and use are the largest sources of global greenhouse gas emissions (IPCC, 2021). Transitioning to renewable energy sources and enhancing energy efficiency are thus critical steps.

This shift not only supports the transition to a low-carbon economy but also aligns with the European Union's (EU) objectives to bolster energy resilience as part of its wider sustainability goals. Energy resilience is a key component of this initiative, focusing on reducing energy dependence on external suppliers, increasing energy security, and promoting economic stability.

The Russian invasion of Ukraine in February of 2022 has massively disrupted global and European energy market. European countries are energy dependent from Russia, and need to become more energy independent if they want to lead the energy transition. For this reason, RePowerEU is the European commission's plan to speed up the green transition and invest massively in Renewable energy and to diversify Europe's energy supplies. The main objectives of this plan are: 1) save energy, 2) accelerate clean energy transition, and 3) diversify energy supplies to phase out dependency on Russian fossil fuels. This European's plan is going to invest 210 billion euros by 2027 to make a massive investment in our energy infrastructure, strengthening the power grid, facilitating RES integration, and increasing the production of bio- and e-fuels.

The integration of energy storage systems (ESS) is vital in achieving these objectives. By enhancing the reliability and efficiency of renewable energy systems, ESS not only helps in managing the internal demand and supply of energy but also reduces the need for energy imports, thereby contributing to energy autonomy. Energy storage technologies play a significant role in addressing these challenges by providing solutions across various sectors, including grid stability, renewable energy integration, industrial generation, micro-grid resilience, and transportation electrification.

However, in many cases and applications, there is no 'silver bullet' solution (i.e., no single technology) which facilitates the needed range of services and simultaneously provides ideal performance, sustainability, reliability and cost. Rather, a combination of various energy storage technologies (electrochemical, chemical, thermal, mechanical and electrical storage) is needed to provide the expected performance in terms of capacity and duration, while also offering the desired flexibility, economic and environmental viability.

This sets the stage for developing hybrid energy storage technologies, where features and characteristics of individual technologies may be combined to find new and viable solutions where the single technologies by themselves fall short. Such a horizontal approach exploits the consideration of hybridization of different energy storage technologies, on either the material, device or system level, has not yet been properly defined, investigated, or deployed to the degree necessary to realize the synergies needed to accelerate the clean energy transition.

2. Vision

The European Union stands at a decisive moment in its transformation toward climate neutrality, industrial leadership, and strategic autonomy. In this era of energy transition and geopolitical uncertainty, the integration of scalable, intelligent, and sustainable energy solutions will define the future of Europe's competitiveness, security, and resilience. Among these, **Hybrid Energy Storage Systems (HESSs)** are emerging not just as supportive technologies, but as **strategic enablers**, capable of bridging sectors, unlocking the potential of renewables, and strengthening Europe's energy system at every level.

From the U.S. Department of Energy[3] and its National Laboratories[4] to European Commission initiatives like the SET-Plan and the Sustainable Energy Days[5], and through the analyses of consultancies such as McKinsey[6], a global consensus is forming around the importance of hybrid energy storage in the energy transition. Institutions at the forefront of research, policy, and systems planning are increasingly recognizing that **hybrid solutions, combining multiple storage technologies, are essential for delivering flexibility, efficiency, and reliability across increasingly complex energy systems.**

The **recognition of hybrid energy storage** systems as a cornerstone of the energy transition presents an **unprecedented opportunity** for the EU Commission and other policymakers to prioritize investments in this critical area. As the world moves towards decarbonization and sustainable energy practices, leveraging the full potential of hybrid storage solutions can accelerate progress towards a cleaner, more resilient, and more equitable energy future.

As Europe moves toward its legally binding target of **carbon neutrality by 2050**, achieving deep integration of variable renewable energy sources (VREs) across sectors and regions will require storage systems that are far more adaptable and capable than conventional technologies alone. In this context, **hybrid energy storage systems offer unique value**: by combining short- and long-duration capabilities[7], electric and thermal storage, and centralized and distributed configurations, HESSs make it possible to align local energy use with system-level needs, from millisecond balancing to seasonal shifting.

[3] U.S. Department of Energy (DOE). 2021. https://www.nrel.gov/docs/fy21osti/77503.pdf

[4] Are Hybrid Systems Truly the Future of the Grid? https://www.nrel.gov/news/features/2021/are-hybrid-systems-truly-the-future-of-the-grid.html

[5] Public debates: Powering the Future: Exploring the Role of Innovative Hybrid Energy Storage Systems in Green Energy Empowerment https://sustainable-energy-week.ec.europa.eu/sustainable-energy-days/powering-future-exploring-role-innovative-hybrid-energy-storage-systems-green-energy-empowerment-2023-06-22_en

[6] Renewable hybrid energy systems as a game changer in India https://www.mckinsey.com/capabilities/sustainability/our-insights/sustainability-blog/renewable-hybrid-energy-systems-as-a-game-changer-in-india

[7] Long Duration Energy Storage refers to storage systems that can discharge energy continuously at their rated power for an extended period, typically ranging from several hours to multiple days.

This transition is not only about technology; it is about **industrial transformation**, **energy system flexibility**, and **democratized energy access**. HESSs will play a decisive role in supporting European industry through decarbonization, enabling smart buildings and prosumers to participate in local energy markets, and facilitating the electrification of all modes of transport, from road and rail to aviation and maritime. Equally, hybrid storage solutions will strengthen the resilience of critical infrastructures and communities, especially as extreme weather, volatile markets, and digitalization place increasing pressure on legacy energy systems.

Our vision is for a **net-zero Europe powered by flexible, intelligent, and storage-integrated infrastructure**, where energy storage is no longer a bottleneck but a **strategic advantage**. In this ecosystem, hybrid storage will be embedded across all layers, from behind-the-meter systems in homes and buildings, to multi-vector industrial hubs, autonomous microgrids, national grids, and transnational electricity markets.

This vision is also one of **technological sovereignty, sustainable value chains, and circular innovation**. Europe must lead the global value chain in designing, producing, and deploying hybrid energy storage solutions, rooted in environmental responsibility, digital optimization, and secure access to critical raw materials. By doing so, hybrid energy storage will support not only energy goals, but also **industrial competitiveness, job creation, and strategic autonomy** in a rapidly shifting geopolitical environment.

In summary, **hybrid energy storage must evolve from a supporting role into a strategic pillar of the energy transition**. Its value lies not only in grid stabilization, but in enabling resilience, decarbonization, and system-level innovation. This roadmap sets out to define that role in full clarifying the services hybrid storage can provide, the technologies it comprises, and the conditions needed to scale its deployment across Europe.

2.1 What the future energy market will look like

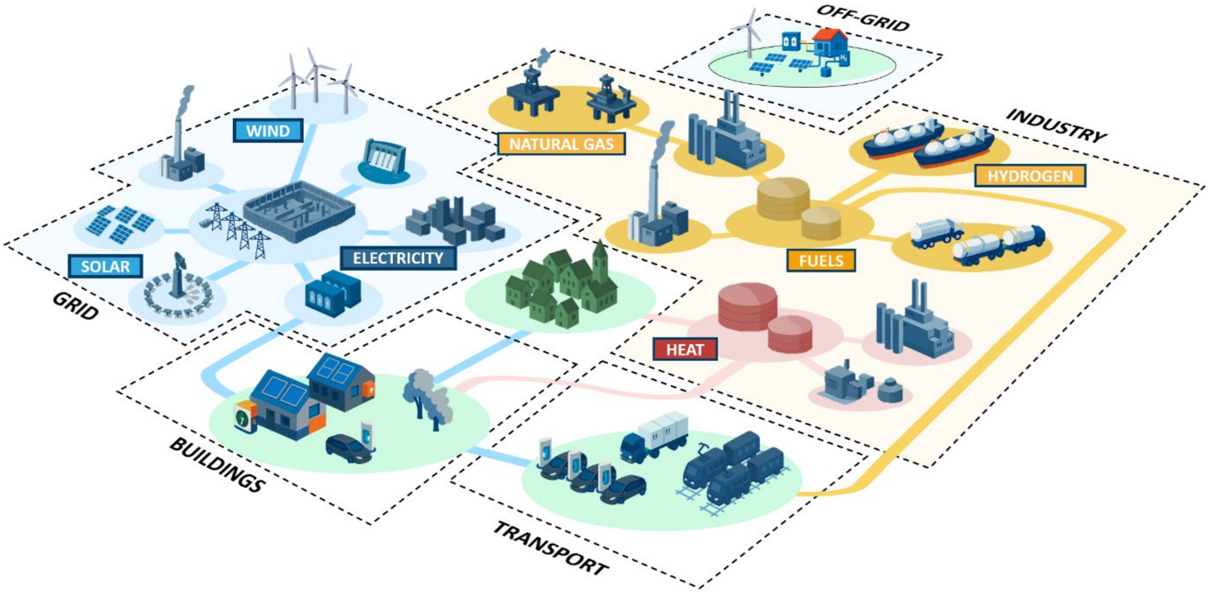


Figure 1. Schematic diagram of the future energy market

Recognizing the diverse and evolving needs of the EU's energy landscape, there is a growing consensus on the importance of hybridizing energy storage systems. Hybrid energy systems, combining multiple storage technologies, promise to deliver versatility, efficiency, and resilience, positioning them as critical enablers of the future low-carbon energy system.

The schematic in Figure 1 illustrates a holistic view of the future energy market anticipated by 2035, highlighting the integrated flow and transformation of energy resources across five main applications: Industry, Grid, Off-grid, Transport, and Buildings. The system is envisioned to be decentralized, disaggregated, and highly dynamic, based on the integration of multiple energy carriers including electricity, heat, hydrogen, biofuels, and e-fuels[8]. It reflects the essence of a plural energy system, in which diversity in energy sources and services becomes a structural asset rather than a complexity burden. Interoperability across energy carriers, vectors, and scales will define the system's resilience, efficiency, and sustainability.

The most profound strategic shift emerging from this evolution is the deepening of **sector coupling**. Seamless integration between the electricity, heating and cooling, transport, and industrial sectors will be indispensable for optimizing resource use, reducing renewable energy curtailment, and achieving system-wide decarbonization targets. Hybrid energy storage systems will enable sectoral interfaces through power-to-heat, power-to-gas, vehicle-to-grid (V2G), and advanced thermal storage applications. By facilitating flexible, bidirectional energy flows across sectors and timeframes, HESSs will become instrumental in balancing fluctuating renewable production with multi-sectoral energy demand. Sector coupling, underpinned by storage flexibility, is not simply an enhancement; it is a necessity for the realization of the

[8] ARUP. Energy systems: A view from 2035
What will a future energy market look like?

European Green Deal, the Fit for 55 Package, and broader international decarbonization commitments.

Parallel to sector coupling, another major evolution is the increasing **need for service stacking**. As power markets evolve, flexibility becomes a scarce and valuable commodity. Traditional storage and generation assets designed for single-purpose operation are becoming economically unsustainable in a low-margin, high-renewable world. In contrast, future energy storage systems will be required to deliver **multiple services**, often simultaneously, to maintain financial viability and support grid operations effectively. A single hybrid asset may need to provide frequency regulation, peak shaving, congestion management, voltage support, and black-start capabilities while participating in wholesale energy and capacity markets. This ability to stack services maximizes asset utilization, strengthens business cases for deployment, and enhances operational efficiency across all levels of the energy system. Regulatory frameworks across Europe are gradually adapting to accommodate and incentivize service stacking, yet further evolution of market designs and system operation models will be essential to fully unlock the potential of flexible hybrid systems.

Ensuring **grid resilience** emerges as a third critical pillar in the future energy system. As the share of variable renewable energy sources such as solar and wind continues to expand, system stability becomes increasingly complex. Maintaining inertia, managing frequency, and absorbing production-demand mismatches across multiple time horizons demands advanced storage solutions capable of fast response and sustained support. Hybrid energy storage systems, by combining fast-reacting technologies like batteries and supercapacitors with long-duration options such as hydrogen, thermal, or mechanical storage, offer a robust framework for this multifaceted requirement. The growing vulnerability of interconnected grids was starkly demonstrated on **April 28, 2025**, when a massive **blackout affected large parts of Spain and Portugal**, impacting millions of citizens, industries, and services. While initial concerns pointed to cyberattacks, subsequently investigations ruled this out. Instead, the incident was attributed to a combination of insufficient reactive power providion, a lack of system inertia due to high renewable penetration, limited interconnection capacity, and critical forecasting errors in solar and wind generation[9]. The event exposed operational weaknesses, including delayed response timers, inadequate spinning reserves, and gaps in voltage control, highlighting the urgent need for improved grid flexibility, enhanced forecasting accuracy, and cross-border coordination. This event underscores the urgent need for distributed, resilient, flexible, and multi-functional storage systems capable of autonomously supporting local grids, stabilizing operations under stress, and preventing cascading failures across interconnected networks.

Importantly, as the energy transition advances, the development of new infrastructures must be complemented by a strategic focus on **preserving and repurposing existing infrastructure**

[9] **International Energy Agency (IEA).** *The Iberian blackout has highlighted the critical importance of electricity security.* May 2025

assets. Legacy infrastructures—such as gas pipelines, fossil fuel power plants, and extensive electricity networks—represent significant investments and can play a critical role in the new energy system. Repurposing fossil fuel plants into grid-support hubs with integrated storage, converting gas pipelines for hydrogen transport, or utilizing existing transmission corridors for integrated electricity-heat-energy networks can accelerate the energy transition while minimizing costs, construction times, and environmental impacts. The inherent value of existing infrastructures must be recognized and leveraged alongside the deployment of new technologies, ensuring a just, efficient, and resilient transformation.

Hybridization of energy storage technologies, combining the strengths of different storage types, offers a promising pathway to enable such flexible, multi-service, cross-sector operation. A detailed technical exploration of hybridization strategies and architectures will be presented in **Section 4**.

The future energy market, therefore, is envisioned not only as a complex, multi-energy system, but as an **ecosystem in which hybridization becomes the norm rather than the exception**. Hybrid energy storage systems (HESSs) are expected to underpin this transformation, offering the versatility and functionality required to meet evolving system demands across all major segments of the energy landscape.

In the industrial and power generation sector, HESSs enhance the flexibility and sustainability of energy-intensive operations. Their integration with thermal energy storage (TES), including sensible, latent, and thermochemical systems, supports not only process heating but also process cooling, co-generation, and better coordination with renewable energy inputs. By enabling multi-energy management, hybrid systems can increase energy efficiency, reduce fossil fuel dependence, and improve dispatchability of clean thermal and electric power.

For transmission and distribution grids, hybrid storage systems could provide a backbone of system stability in an increasingly decentralized and renewable-driven energy landscape. They enable critical services such as frequency and voltage regulation, congestion relief, and inertia support across multiple time scales. By combining power-dense and energy-dense technologies, HESSs enhance grid responsiveness and reduce operational strain. As Variable Renewable Energy (VRE) penetration increases, hybrid systems help absorb and stabilize imbalances between production and demand. Given that current and planned storage capacity remains a fraction of generation capacity, the role of HESSs is best understood as enhancing system responsiveness, flexibility, and reliability, not replacing dispatchable generation, but complementing it. In this evolving grid environment, HESSs help manage both routine variability and exceptional events, while improving asset longevity and reducing the stress on infrastructure.

In **off-grid and remote systems**, HESSs empower energy autonomy and resilience, particularly in regions with harsh climates, weak grid access, or seasonal supply-demand mismatches. From cold-weather operations requiring high heating loads to remote island microgrids balancing solar supply and cooling demands, hybrid storage solutions are able to adapt flexibly to local needs. Their role is key in decarbonizing isolated systems while maintaining affordability and reliability.

In the transport sector, hybrid storage supports the ongoing transformation of mobility across road, rail, maritime, and aviation. Through combinations such as batteries and fuel cells, or hybrid propulsion systems in urban and long-haul transport, these solutions help extend driving range, enhance infrastructure flexibility, and reduce environmental impact. As energy storage becomes embedded in charging networks and transport fleets, hybrid systems will be indispensable to decarbonizing mobility while minimizing stress on the power grid. They also offer promising pathways to electrify and decarbonize challenging transport segments such as aviation, maritime, rail, and heavy-duty vehicles, where single-technology solutions remain limited.

In buildings, HESSs will play a growing role in dynamic energy management across both residential and commercial applications. By combining electricity and thermal storage, often integrated with reversible heat pumps, smart controls, and onsite renewable generation, HESSs allow buildings to manage both heating and cooling demands more effectively. These systems support load shifting, maximize the self-consumption of renewable energy, improve local energy resilience, and enable participation in emerging demand response and flexibility markets. As buildings evolve into active energy hubs, hybrid storage will be key to enhancing comfort, reducing costs, and supporting grid stability.

Together, these five sectors represent **the primary arenas where HESSs can deliver system-wide value**, not just as storage, but as integrated components of a more flexible, resilient, and decarbonized energy system. Their application will shape how energy is produced, stored, exchanged, and consumed across Europe, linking technologies, infrastructures, and sectors in unprecedented ways.

2.2 Technical considerations for a fully renewable-driven energy system

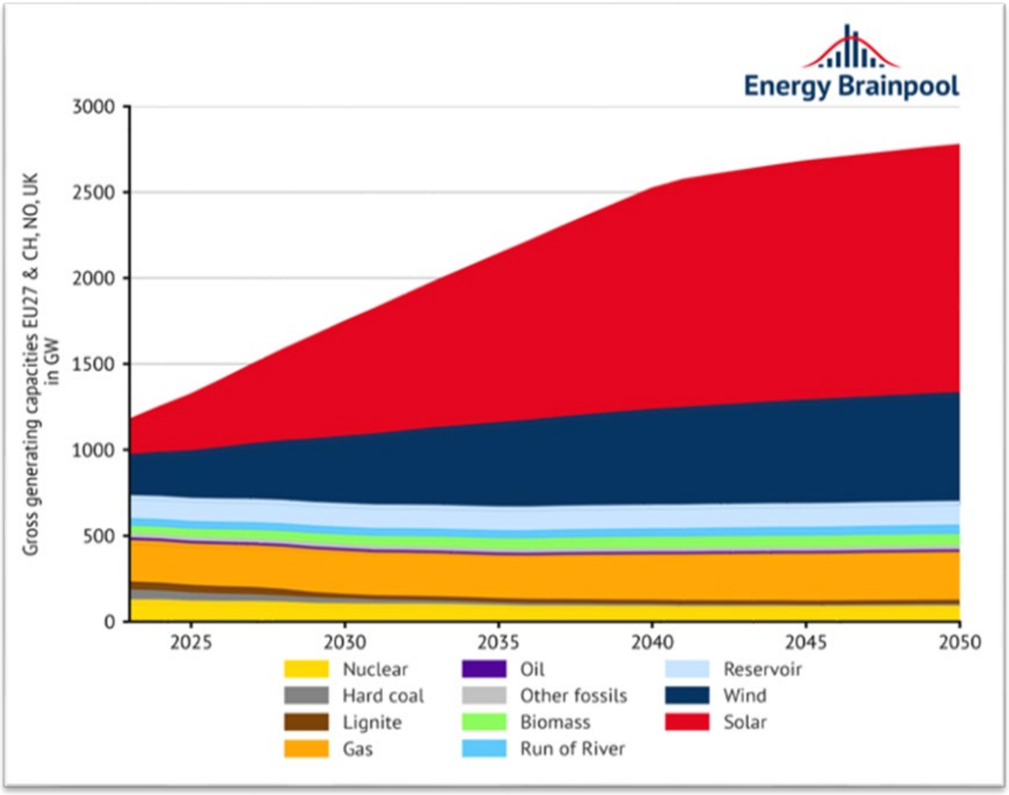


Figure 2. Installed generation capacities in EU-27 (plus NO, CH and UK) by energy source / SOURCE: Energy Brainpool, 2022; EU Reference Scenario, 2021; entso-e, 2022

Figure 2 shows the projected evolution of gross electricity generation capacity in the EU27, UK, Norway, and Switzerland from 2020 to 2050. By mid-century, **solar PV capacity is expected to exceed 1500 GW**, with **wind capacity reaching 500 GW**. Together, these variable renewable energy (VRE) sources will dominate Europe's power mix, thanks to declining costs and rapid deployment. However, their non-dispatchable nature presents major technical and systemic challenges, particularly in **balancing supply and demand**, **ensuring reliability**, and **maintaining grid stability**.

In 2050, **nuclear, biomass, concentrating solar thermal power, and hydropower technologies are expected to be maintained** at the same capacity levels as in 2030 for example.

Coal-fired power plant capacity will **decrease by more than 80% by 2050**. Which is an expected result of the zero-emissions policies.

The growing reliance on electricity as the backbone of Europe's energy system reflects deep structural change. While electricity currently accounts for ~23% of the EU's final energy consumption, this is projected to reach **around 50% by 2050**, according to the EU Reference Scenario. This electrification, driven by sector coupling and decarbonization, will significantly increase pressure on grid infrastructure, flexibility mechanisms, and energy storage systems.

Electricity Storage and Grid Resilience

To enable the integration of high shares of VRE, energy storage must operate across a wide range of **technical time scales**: from **milliseconds for frequency regulation**, to **hours and days for peak shifting**, and **weeks or months for seasonal balancing**.

Battery systems, particularly lithium-ion and flow batteries, are being rapidly deployed for intra-day balancing and ancillary services. **Pumped hydro storage (PHS)** remains the most widely used form of large-scale storage, especially in countries like Norway where topography supports reservoir-based systems with flexible discharge durations. In most of Europe, however, PHS is typically limited to **daily cycles** with discharge durations of 6–10 hours (e.g., the Goldisthal PHS plant in Germany)[10].

Compressed air energy storage (CAES) systems, like those at **Huntorf[11]** and **McIntosh[12]**, have demonstrated commercial viability but are similarly used for **daily balancing**, not seasonal storage. **Long-duration storage**, critical to align seasonal VRE availability with demand, must increasingly rely on **hydrogen, ammonia**, or **thermal energy storage**.

The growing share of inverter-based renewable generation introduces a range of **technical challenges** that storage must help mitigate. These include:

- **Abrupt generation decreases**, such as during rapid cloud cover or wind lulls, which require immediate compensation.
- **Loss of voltage regulation capacity**, since most VRE sources do not provide consistent voltage support.
- **Loss of frequency regulation capacity**, due to the low inertia of converter-based resources, making grids more sensitive to sudden imbalances.
- **Reduced power reserve**, which becomes harder to ensure as synchronous generators are displaced by VRE—though this issue often stems from **market design** limitations rather than technical infeasibility.
- **Transmission congestion**, particularly where VRE deployment outpaces grid expansion (which can take up to a decade). Contrary to some misconceptions, **storage can help alleviate congestion**, especially when deployed locally near generation or demand centers.
- **Decreased grid inertia**, as the shift to power-electronic interfaces reduces the system's natural resistance to frequency fluctuations.

According to **IRENA**, these challenges can be addressed through enhanced **power system flexibility**, defined as the ability to respond to variability and uncertainty across time scales while maintaining system reliability. Key services include:

- **Power reserve**, especially for fast-ramping events,
- **Voltage and frequency regulation**, threatened by the low inertia of inverter-based renewables,
- **Curtailment avoidance**, to ensure VRE utilization is maximized,
- **Congestion management**, especially where VRE development outpaces transmission planning.

[10] https://powerplants.vattenfall.com/goldisthal/
[11] https://www.sssgears.co.uk/en/case-studies/huntorf/
[12] https://caes.pnnl.gov/

Addressing these issues requires not only individual technologies but integrated **hybridization strategies**. These involve combining conventional and renewable generation with multi-vector energy storage systems to ensure stable, secure, and efficient grid operation. **Hybrid Energy Storage Systems** would potentially be uniquely suited to deliver these capabilities, providing fast-acting and long-duration services through a single optimized platform.

Heat and Cold Storage

Heat and cold storage technologies are vital for optimizing electrified heating and cooling systems, improving industrial energy efficiency, and enhancing the performance of district energy networks. **Thermal energy storage (TES)** technologies come in three main forms:

- **Sensible heat storage** (e.g., water tanks or molten salt),
- **Latent heat storage** (e.g., ice-based systems),
- **Thermochemical storage** (high-density materials suitable for industrial use).

TES is widely applied in **district heating and cooling networks**, where excess thermal energy—often from solar thermal fields or industrial waste heat—is stored during off-peak periods and delivered later via insulated distribution systems. For instance, the **La Défense cooling system in Paris**[13] stores ice at night to meet daytime demand, flattening electricity use and improving system balance.

TES also plays a growing role in **domestic hot water systems** and **cogeneration (CHP) plants**, where it increases operational flexibility and enables plants to generate electricity during periods of high power prices while still meeting thermal loads as needed. In **industry**, TES supports waste heat recovery and process decarbonization, offering a low-cost pathway to improve energy use in sectors striving for net-zero emissions.

In the power sector, **concentrated solar thermal power (CSTP)** plants have proven the feasibility of **large-scale TES**—using molten salt to store solar heat for 8–15 hours, enabling dispatchable power generation. These systems have inspired **Carnot batteries**, where renewable electricity is converted into heat and stored for reconversion, offering a novel form of long-duration storage.

TES delivers multiple system-level benefits:

- **Long-duration energy shifting**, especially for heating networks and CSTP,
- **Peak shaving**, by storing thermal energy during low demand and releasing it during peaks,
- **Energy efficiency**, particularly through **waste heat recovery** and hybridized industrial systems.

Importantly, **cold storage** is emerging as a key flexibility asset. Large-scale systems can store chilled water or ice during low-load periods—typically at night—for use during peak daytime cooling demands. This approach, already implemented in several European cities, reduces grid stress and improves the load factor of electricity infrastructure.

TES technologies are highly adaptable and can be integrated across a wide range of energy systems, helping to bridge thermal

[13] https://www.suc-energie.fr/suc-le-reseau-de-froid-de-la-defense

and electrical domains and support deeper sector coupling.

Fuels and Chemical Storage: Hydrogen, E-fuels, and Beyond

The storage and use of chemical energy carriers, especially **hydrogen**, is expected to play a strategic role in the long-term energy transition. According to the European Commission's 2018 strategic vision and subsequent *Fit for 55* impact assessments, hydrogen's share in the EU energy mix is projected to grow from **less than 2% today to 13–14% by 2050**. These projections were reaffirmed in the 2030 *Climate Target Plan*, and several EU Member States, including Germany, are considering **green hydrogen imports** from countries with favorable renewable resources, such as Namibia[14,15].

Hydrogen will be primarily produced via **electrolysis**, especially through **Power-to-Gas (P2G)** processes during periods of excess electricity generation. The resulting hydrogen can then be **reconverted to electricity** during demand peaks or used as a **green fuel** in transport and industrial heating.

In the **transportation sector**, hydrogen and its derivatives—including **synthetic fuels** produced from CO_2 and H_2—are essential for aviation, marine transport, and heavy-duty vehicles where direct electrification remains impractical. **Biofuels**, already compatible with existing infrastructure, also continue to play a role. While their storage does not require new technologies, they remain relevant for decarbonizing energy-dense applications.

It is important to distinguish:

- **Hydrogen as a chemical feedstock**, e.g., for steel, ammonia, methanol, and fertilizers,
- **Hydrogen as an energy vector**, for electricity generation, heat provision, and energy balancing.

Storage of hydrogen—in gaseous, liquid, or chemically bound forms—offers **seasonal-scale flexibility** not achievable with electrochemical storage. It supports:

- **Sector coupling**, linking electricity with heat, mobility, and industrial demand,
- **Grid balancing**, by absorbing surplus electricity and supplying energy during peaks,
- **Energy security**, through both domestic production and diversified imports.

However, several **technical and economic challenges** remain. Hydrogen storage and distribution face barriers related to **cost**, **safety**, and **conversion efficiency**. Innovations in **solid-state storage**, **metal hydrides**, and **reversible fuel cells** are critical to enabling hydrogen's effective and safe integration into Europe's future energy system.

Unlike hydrogen, synthetic and biofuels typically rely on **existing storage and distribution infrastructure**. The key integration challenge lies not in their storage, but in **power-to-fuel conversion** and the **flexible use of stored fuels** for electricity or heat—especially in dispatchable, low-carbon energy applications.

[14] https://www.dw.com/de/gr%C3%BCner-wasserstoff-namibias-mammutprojekt-wird-konkret/a-65748116

[15] https://gh2.org/countries/namibia

The energy transition will not be defined by a single technology, but by the **integration of multiple energy carriers**, **diverse storage forms**, and **cross-sectoral infrastructure**. Hybrid energy storage systems, capable of delivering stacked services and bridging energy domains, will be central to achieving Europe's climate and energy ambitions. By combining the strengths of electricity, thermal, and chemical storage—and aligning them with real-world demand patterns—HESSs provide the foundation for a sustainable, secure, and flexible energy future.

2.3 Economic and industrial policy ambitions for storage roll-out

The large-scale deployment of HESSs is not only a technical imperative, but also a cornerstone of Europe's broader industrial, economic, and strategic ambitions. As Europe accelerates its transition toward a climate-neutral energy system, the energy storage sector is increasingly recognized as a **strategic industry**, capable of generating skilled employment, fostering domestic innovation, and strengthening **technological sovereignty**.

A robust storage industry is essential to Europe's **global competitiveness** in clean energy. This includes strengthening the **manufacturing of core components** (e.g., batteries, power electronics, thermal and hydrogen systems), developing advanced control software, and scaling up **system integration and digital energy services**. The EU's industrial policy places growing emphasis on **"Made in Europe" solutions**, ensuring that the value chain—from materials and design to production and deployment—supports the **resilience of European supply chains**.

Storage, and particularly **hybrid configurations**, enable European companies to develop differentiated, high-performance solutions tailored to diverse grid and sectoral needs. These innovations, when scaled, can become major export technologies, mirroring the trajectory of wind and solar over the past two decades.

While the sections below outline key elements of Europe's economic and industrial policy ambitions, namely public investment, regulatory frameworks, and skills development, a more detailed and comprehensive analysis is presented in the **Strategic Research and Innovation Agenda (SRIA) for Hybrid Energy Storage (HES)[16].**

Public Investment and Financial Incentives

The European Commission and national governments are stepping up **funding mechanisms** and **incentive schemes** to support energy storage deployment. Instruments include:

- The **EU Innovation Fund**, which supports first-of-a-kind commercial demonstration projects, especially for long-duration and hybrid storage technologies;
- The **Connecting Europe Facility (CEF)**, facilitating infrastructure investment;
- **IPCEIs** (Important Projects of Common European Interest), enabling public support for industrial-scale innovation;
- EIB and national green investment banks, offering concessional financing.

In addition, state aid frameworks have been relaxed to allow greater support for strategic technologies under the **Net-Zero Industry Act**, with energy storage identified as a key priority. Public–private partnerships and blended finance are increasingly leveraged to de-risk early deployment while crowding in private capital.

[16] Scipioni, R. et al. *D3.6 – "SRIA for hybridisation of Energy Storage",* StoRIES Consortium, June 2025

A Fit-for-Purpose Regulatory Framework

An enabling regulatory environment is essential to unlock investment in energy storage. Current reforms aim to:

- **Clarify the role of storage** in electricity market design, including its eligibility to provide and be remunerated for stacked services (e.g., balancing, capacity, ancillary),
- **Streamline permitting** and interconnection processes for storage facilities, especially hybrid and co-located systems,
- **Ensure fair grid access**, cost-reflective tariffs, and clear ownership models,
- Harmonize safety, quality, and performance **standards across technologies and borders**.

Efforts are also underway to improve the **valuation of flexibility** in energy markets and to develop **long-term contracting mechanisms** that support investment in capital-intensive, long-duration assets.

Skills, Jobs, and Innovation Capacity

Europe's competitiveness in energy storage also depends on its ability to develop and retain world-class talent. National and regional policies are beginning to address **skills shortages** in the battery, hydrogen, and digital energy sectors. Programs to support **vocational training, upskilling, and reskilling** are key to building a resilient workforce for hybrid energy systems.

Meanwhile, **European universities, research centers, and technology platforms** are expanding R&D on materials science, hybrid architectures, control systems, and grid integration. Continued support for **open innovation ecosystems**, living labs, and pilot projects will help bring advanced HESS technologies from lab to market.

2.4 Societal considerations for a transparent, just, and sustainable energy transition

A successful energy transition must be not only technological and economic, but also **socially inclusive, transparent, and participatory**. Public engagement plays a crucial role in shaping energy policy and building trust in new infrastructure. Across Europe, governments and institutions are increasingly using **digital platforms, public consultations, and open data tools** to improve transparency and ensure that local communities are informed and involved in the development of energy projects. Meaningful participation helps align energy planning with societal needs, fosters acceptance, and ensures that transition strategies reflect the values and expectations of citizens.

Ensuring a **just transition** is central to Europe's climate and energy policy. This means making sure the benefits of clean energy, such as lower emissions, improved air quality, and economic opportunities, are accessible to all, particularly vulnerable or historically underserved communities. Addressing **energy poverty**, ensuring **affordability**, and supporting workers and regions affected by the decline of fossil fuel industries are critical components of this effort. Strategic workforce planning, including **job creation, training, and reskilling**, is essential to ensure that those affected by sectoral shifts are not left behind, but are empowered to participate in the green economy.

Sustainability goes beyond decarbonization. The environmental and social impacts of new technologies and infrastructure must be evaluated across their **entire lifecycle**, from raw material extraction to manufacturing, deployment, and end-of-life. This includes assessing **resource availability, geopolitical risks, and recyclability**. Hybrid energy storage systems, like other clean energy technologies, must be developed and deployed with attention to **environmental justice, worker safety**, and the **health and well-being** of communities. Policies should support transparent decision-making, robust impact assessments, and the inclusion of **cultural values and local priorities**, particularly in areas facing rapid energy system changes. A transparent, just, and sustainable energy transition requires not only innovation in technology, but also a commitment to equity, accountability, and shared societal benefit.

3. Technology landscape

The value of energy storage lies not only in its ability to deliver electricity on demand but also in the broad range of services it can provide across timeframes, sectors, and scales. Assessing and comparing Energy Storage Systems (ESSs) requires careful consideration of their physical characteristics, operational behavior, and service potential, all within a context shaped by national policies, market structures, and system needs. One of the unique advantages of ESSs is their ability to deliver stacked services across short-term (milliseconds to minutes), mid-term (hours), and long-term (days to weeks) durations. However, this potential must be matched with accurate valuation methodologies that respect the inherent physical and control constraints of each technology.

In the European Union, energy storage technologies span a diverse and evolving spectrum. According to the IHA 2024 World Hydropower Outlook[17], **pumped storage hydropower (PSH)** remains the dominant form of grid-connected storage, with over **70 TWh**[18] of installed energy capacity and **54 GW** of power output, expected to double by 2050. These systems, while primarily designed for daily cycling, provide crucial services such as load shifting, inertia, and frequency regulation. In countries like Norway, reservoir-based PSH can support inter-day and even multi-day balancing.

At the same time, **battery storage technologies** are expanding rapidly. If all announced projects are realized, the combined production capacity from battery cell companies and startups is expected to amount up to **886 GWh/year** in Europe by 2030[19]. While **lithium-ion batteries** dominate in mobile and short-duration stationary applications, alternatives such as **sodium-ion**, **flow batteries**, and **supercapacitors** offer specific advantages in terms of cost, lifecycle, safety, and scalability. Batteries are primarily used today for power quality, frequency response, and short-term peak shaving.

Thermal energy storage (TES) is gaining increasing importance, especially in **district heating and cooling networks**, and as part of **hybrid solutions** that combine heat and electricity. TES includes technologies like molten salts, phase change materials, and thermochemical systems, each serving different time scales and operating temperature ranges (Figure 3b).

Chemical storage, particularly **hydrogen and synthetic fuels**, plays a critical role for inter-seasonal applications and sector coupling. Hydrogen can be produced via electrolysis using excess renewable electricity and stored for reconversion or used directly in industrial, mobility, or heating applications. These forms of storage provide valuable pathways for managing excess generation, decarbonizing hard-to-electrify sectors, and enhancing energy system resilience.

[17] https://www.hydropower.org/publications/2024-world-hydropower-outlook
[18] https://www.iea.org/energy-system/renewables/hydroelectricity
[19] https://batterieseurope.eu/wp-content/uploads/2023/09/Batteries-Europe_Research-and-Innovation-Roadmap-2023_.pdf

△ Faces geologic constraints[4] | Not enough public datapoints to obtain a reliable value | Less Desirable → More Desirable

Inter-day | Can function as both | Multi-day/week

Duration	Energy storage form	Technology	Nominal duration, hrs	LCOS[5], $/MWh	Min. deployment size, MW	Average RTE, %	TRL
Inter-day	Mechanical	Traditional pumped hydro (PSH) △	0–15	70–170	200 – 400	70–80	9
		Novel pumped hydro (PSH)	0–15	70–170	10–100	50–80	5-8
		Gravity-based △	0–15	90–120	20–1,000	70–90	6-8
		Compressed air (CAES) △	6–24	80–150	200–500	40–70	7-9
		Liquid air (LAES)[1]	10–25	175–300	50–100	40–70	6-9
		Liquid CO2[1]	4–24	50–60	10–500	70–80	4-6
Multi-day / week	Thermal	Sensible heat (e.g., molten salts, rock material, concrete)[2]	10-200[2]	300	10–500	55–90	6-9
		Latent heat (e.g., aluminum alloy)	25–100	300	10–100	20–50	3-5
		Thermochemical heat (e.g., zeolites, silica gel)	XX	XX	XX	XX	XX
	Electrochemical	Aqueous electrolyte flow batteries	25–100	100-140	10–100	50–80	4-9
		Metal anode batteries	50–200	100	10–100	40–70	4-9
		Hybrid flow battery, with liquid electrolyte and metal anode (some are Inter-day)[2,3]	8–50[2]	XX	>100	55–75	4-9

Figure 3. LDES technologies grouped based on physical characteristics and in varying stages of development. Reproduced from the U.S. Department of Energy's *Pathways to Commercial Liftoff: Long Duration Energy Storage* (2023)[20], with permission from the U.S. Department of Energy.

Long Duration Energy Storage (LDES)

As renewable penetration increases and reliance on variable sources like wind and solar grows, the need for **Long Duration Energy Storage (LDES)** becomes more urgent. While there is no single definition, LDES generally refers to systems capable of shifting energy over **more than 10 hours**, with subcategories:

- **Inter-day LDES**: ~10–36 hours,
- **Multi-day/week LDES**: ~36–160 hours,
- **Seasonal balancing**: >160 hours or multiple months.

A key insight from the U.S. Department of Energy[20] and other modeling efforts is that in deeply decarbonized systems, LDES capacity additions may rival or even exceed all other generation technologies except wind and solar. LDES is essential to:

- Provide clean dispatchable capacity during low VRE output,
- Enable bulk energy shifting over days to align generation with demand,
- Improve resilience during multi-day outages or extreme events,
- Defer costly grid reinforcement where congestion or infrastructure limits arise,
- Support behind-the-meter peak management for large commercial or industrial loads.

It is important to note that what qualifies as "long-duration" can differ depending on the energy carrier. A 10-hour storage system may be considered long-duration for **electrical systems** but relatively short for **thermal or chemical storage** applications, which often deal with inter-day to seasonal scales. Therefore, while the definitions provided here are useful for comparative purposes, they are applied as part of a **hybrid energy storage systems** perspective, one that aims to bridge technologies and services across durations, sectors, and use-cases.

[20] **U.S. Department of Energy.** *Pathways to Commercial Liftoff: Long Duration Energy Storage.* March 2023.

In this roadmap, we adopt a working definition for hybrid energy storage systems (HESSs) based on duration thresholds:

- **Short-duration**: < 10 hours,
- **Medium-duration**: 10–48 hours,
- **Long-duration (LDES)**: > 48 hours.

These categories reflect a functional and system-oriented view that can guide planning, hybridization strategies, and policy design. The thresholds are meant to accommodate the integration of complementary technologies with differing response speeds and storage depths across energy forms. This classification aligns with DOE and IRENA practices but is tailored to hybrid systems that combine storage forms with different response times and efficiencies. It enables:

- Co-optimization of service stacking (fast regulation + slow firming),
- Improved cost-efficiency by allocating functions to the most suitable technology,
- Design of multi-service systems (e.g., frequency regulation + peak shifting + outage resilience).

A dedicated schematic (Figure XX) illustrates the performance envelope of hybrid systems across durations, technologies, and services.

For example, while **pumped hydropower** and **CAES** are mature mechanical options typically suited to inter-day shifting, their deployment is geographically constrained. **Thermal LDES**, such as molten salts and thermochemical storage, offer long-duration potential especially in heating and industrial sectors. **Electrochemical options**, including **flow batteries** and **metal-air batteries**, are progressing from lab to early commercial stages and benefit from modularity and flexibility.

Hydrogen-based storage is also positioned for seasonal applications and sector integration, although competing demands (e.g., for industrial hydrogen or transport fuels) may limit its availability for grid balancing. Therefore, LDES technologies must be assessed not in isolation, but in terms of their systemic contribution and complementarity.

A Distinction Between LDES and LTES

For the first time in a strategic roadmap, we introduce a distinction between **Long Duration Energy Storage (LDES)** and **Long-Term Energy Storage (LTES)**, based on their discharge duration and energy retention characteristics. This classification helps structure research and innovation efforts while recognizing that thresholds may differ across storage types—electrochemical, thermal, chemical, or mechanical.

LDES refers to systems capable of discharging energy continuously at rated power for several hours to multiple days. These systems are vital for daily to weekly balancing, firming renewable output, and supporting reliability during periods of stress. Typical LDES examples include electrochemical systems like flow batteries, chemical solutions such as P2X, and mechanical or thermal solutions that generate electricity (e.g., CAES, pumped hydro, molten salts).

LTES, in contrast, emphasizes the ability to retain stored energy over much longer durations—weeks, months, or seasons—with minimal loss. The focus is on energy retention rather than continuous discharge. LTES technologies include solid-state or molten thermal storage, hydrogen and synthetic fuels, and other chemical energy carriers. These systems are crucial for seasonal balancing, decarbonizing industrial heat, and enhancing energy sovereignty.

Recognizing this distinction helps clarify technology pathways and align specific innovations to the most appropriate roles in the future energy system.

The Role of Hybrid Storage in Enabling LDES

Despite progress, mature forms of LDES remain limited in commercial availability and cost-effectiveness. One promising strategy is **hybridization**: combining short-duration, high-efficiency storage (like batteries or supercapacitors) with longer-duration, slower-response systems (like hydrogen or TES). Hybrid systems can optimize performance by covering a broader spectrum of timeframes and service types, while balancing cost, efficiency, and operational constraints. As later discussed in Section 4, hybridization enables service stacking, enhances sector coupling, and improves both the technical and economic feasibility of deploying LDES in diverse energy environments.

This technology landscape overview sets the stage for a more detailed classification of storage technologies in the following subsections:

- Electrochemical Energy Storage (**EES**),
- Thermal Energy Storage (**TES**),
- Chemical Energy Storage (**CES**),
- Mechanical Energy Storage (**MES**),
- Superconducting Magnetic Energy Storage (**SMES**).

Each category will be examined based on physical principles, performance characteristics, maturity levels, and potential contributions to Europe's energy transition.

3.1 Electrochemical Energy Storage

Electrochemical energy storage (EES) systems, such as batteries and supercapacitors, are essential in today's energy landscape, offering efficient solutions for storing and releasing electrical energy through electrochemical reactions. Central to EES systems are electrodes and electrolytes, facilitating ion transfer during charging and discharging cycles, critical for applications ranging from portable electronics to electric vehicles and renewable energy grid integration. Lithium-ion batteries, notable for their high energy density and longevity, epitomize the advancement in EES, addressing the demand for sustainable and efficient energy storage solutions. As technology evolves, research focuses on enhancing materials to develop safer, more energy-dense, and cost-effective EES options, promising a future of sustainable energy management and utilization.

Batteries

Batteries are electrochemical devices that store energy in chemical form and convert it back into electricity. Among the different types of batteries, lithium-ion (Li-ion), sodium-ion (Na-ion), and flow batteries stand out due to their distinctive characteristics, applications, and potential for future development. Furthermore, emerging battery technologies promise to address the limitations of current systems, offering new possibilities for both mobile and stationary applications.

Lithium-ion batteries

Lithium-ion batteries (LIBs) have become the pillar of modern portable electronics, electric vehicles (EVs), and are increasingly used in stationary storage applications to stabilize the grid and store renewable energy. Their popularity stems from a high energy density (150-200 Wh/kg LFP, 200-300Wh/kg NMCx), long cycle life (15,000 Cycles for LFP, BESS 6.25MWh in a standard 20-foot container[21]), and relatively low self-discharge rates. These attributes make Li-ion batteries ideal for mobile applications where weight and space are critical constraints, as well as for short-duration stationary storage applications that require quick response times and high-power output. The predominant chemistry used in BESS applications is $LiFePO_4$ (LFP), that exhibits longer cycle life, better structural and thermal stability, resistance to thermal runaway when compared to NMCx based chemistry. LFP cells ($59/kWh) is also cheaper[22] compared to NMCx cells ($68.6 kWh) due to the price difference of the constituent elements. However, issues such as lithium availability and its cost, and the need to minimize safety risks associated with thermal runaway have driven research into alternative technologies. For FTM applications cell capacities are steadily increasing from 300Ah to > 500Ah per cell to improve volumetric energy density while reducing costs (fewer connectors / complexity) while the form factor is standardizing around 20 ft containers (6MWh+ capacity)[23,24] for ease of logistics inclusive of the DC Block. Multiple GWh

[21] https://www.lifepo4-battery.com/News/catl-releases-tianheng-ess-zero-decay.html
[22] https://www.reuters.com/markets/commodities/battery-cell-prices-fall-record-low-september-says-report-2024-10-30/
[23] https://cnevpost.com/2024/04/10/catl-launches-tianheng-energy-storage-system/
[24] https://www.ess-news.com/2024/09/06/envision-pushes-energy-storage-density-to-new-highs-with-8-mwh-20-foot-container/

projects have recently been awarded[25,26,27,28] utilizing such containerized modular containerized BESS units, and most recently a 19GWh tender award to CATL's TENER units[29].

Sodium-ion batteries

Sodium-ion batteries (SIBs) emerge as a promising alternative, leveraging the abundant and widely available sodium element. While they share a similar working principle to Li-ion batteries, Na-ion technologies offer potential cost advantages and less environmental impact. Their cell level energy density is lower (90-140Wh/Kg) than that of Li-ion batteries, which currently limits their use in weight-sensitive applications like EVs. However, they hold great promise for stationary storage applications, particularly for long-duration energy storage due to their safety, assumed cost-effectiveness (no Ni,Co,Li), and material availability (Na). Chemistries commercialized include $Na_xT_MO_2$ layered oxides (T_M = transition metals), Polyanionic cathodes such as NVPF ($Na_3V_2(PO_4)_2F_3$), NFS ($Na_2Fe(SO_4)_2$) and NFPP ($Na_4Fe_3(PO_4)_2P_2O_7$), Prussian blues and its analogues. HiNa[30] produces Na-Fe-Mn-Cu oxide-based cells while Tiamat[31] produces NVPF based cells and ZOOLNASM[32] produces NFS based cells. BYD has chosen to go with NFPP[33] in its MC Cube-SIB ESS[34](2.3MWh)[35] product. BYD has a 30GWh planned Na-ion factory in the works. Compared to LIBs, FTM field deployment of SIBs lags in scale in the 100MWh range[36]. The primary reason for this lag is that its prices are not at par yet with those of LIBs due to the underdeveloped NIBs material supply chain compared to LIBs. Recently NFPP cathode material production has been scaled to 10,000mt/annum with eventual plans for 100,000mt/annum[37].Costs of SIBs are expected to drop with scaleup of both cathode and anode production in the near future.

Flow batteries

Redox flow batteries (RFBs) are known for their unique design that decouple energy storage from power generation, excel in scalability and long-duration energy storage applications. They store chemical energy in external tanks, allowing system capacity to be easily expanded by simply increasing the size of the tanks. This makes them particularly suitable for large-scale stationary applications, such as grid energy storage, where they could provide several hours to days of energy supply, making them ideal for integrating intermittent renewable energy sources like wind and solar power. Although their energy density (30-40Wh/l[38]) is lower compared to Li-ion batteries (>350Wh/l), making them unsuitable for most mobile applications, their long lifespan (>20,000 Cycles, > 20 years), and the ability to deliver sustained

25 https://www.teslarati.com/tesla-megapacks-europes-largest-energy-storage/
26 https://www.energy-storage.news/giga-storage-contracts-sweco-to-design-2-8gwh-belgium-bess/
27 https://www.teslarati.com/tesla-intersect-power-15-3-gwh-capacity-megapack/
28 https://www.pv-magazine-india.com/2025/02/18/byd-to-supply-12-5-gwh-of-battery-storage-in-saudi-arabia/
29 https://masdar.ae/en/news/newsroom/masdar-announces-preferred-contractors-and-suppliers
30 https://www.hinabattery.com/index.php?catid=28
31 https://www.tiamat-energy.com/wp-content/uploads/2025/02/202502_datasheet-pristmatic-cell.pdf
32 http://www.zoolnasm.com/?m=home&c=Lists&a=index&tid=33
33 https://www.linkedin.com/pulse/byds-nfpp-na-ion-battery-could-30-cheaper-than-lfp-jerry-8td5c/
34 https://www.energy-storage.news/byd-launches-sodium-ion-grid-scale-bess-product/
35 https://news.metal.com/newscontent/103070079/BYD-Launches-Worlds-First-High-Performance-Sodium-Ion-Battery-Energy-Storage-System:-MC-Cube-SIB-ESS
36 https://www.pv-magazine.com/2024/08/08/sineng-electric-launches-worlds-largest-sodium-ion-battery-storage-project/
37 https://www.metal.com/en/newscontent/103095831
38 Fraunhofer Alternative Battery Technologies Roadmap 2030+

power over extended periods are significant advantages. The world's largest deployment is a 700MWh vanadium redox flow battery (VRFB) in China.[39]

Emerging battery technologies

Innovation in battery technology continues to thrive, with several emerging solutions showing promise for both stationary and mobile applications. Solid-state batteries, which replace liquid electrolytes with solid ones, are one of the most anticipated advancements. They offer the prospect of higher energy densities, improved safety, and longer lifespans compared to conventional Li-ion batteries. Solid-state batteries are considered a breakthrough for electric vehicle applications and could revolutionize portable electronics and stationary storage systems. Metal-air batteries, particularly lithium-air, iron-air and zinc-air, are another area of significant interest. These batteries have the potential for extremely high energy densities, surpassing that of Li-ion batteries. However, challenges such as short cycle life and slow reaction rates (which makes them more suitable to LDES) need to be overcome before they can be commercially viable. For stationary applications, especially long-duration storage, the development of new chemistries and technologies, such as redox flow batteries beyond vanadium and hybrid systems, continues to offer hope for more efficient, durable, and cost-effective energy storage solutions.

Supercapacitors

Supercapacitors are revolutionizing energy storage with their unique ability to rapidly store and release energy through the formation of an electrochemical double layer at the electrode-electrolyte interface. Unlike traditional batteries, which rely on chemical reactions, supercapacitors store energy in an electric field, allowing for ultra-fast charging and discharging cycles. This grants them exceptional power density (but very low energy densities), virtually unlimited cycle life, and resilience to extreme temperatures.

These attributes make supercapacitors well-suited for supplementing systems that require quick bursts of power, such as regenerative braking in electric vehicles, grid stabilization, and smoothing out power fluctuations in renewable energy systems, though their limited energy storage capacity typically requires integration with other storage technologies. Additionally, supercapacitors find use in consumer electronics, where their rapid charging capabilities enhance user experience.

[39] https://www.energy-storage.news/rongke-power-completes-grid-forming-175mw-700mwh-vanadium-flow-battery-in-china-worlds-largest/

3.2 Thermal Energy Storage

Thermal energy storage (TES) technologies have broad technical characteristics, and they can be applied to meet from hours to even months of energy storage needs. According to the physical principle through which thermal energy is stored, TES technologies are divided into three main groups: sensible heat storage (SHS), latent heat storage (LHS) and thermochemical storage (TCS)

·**Sensible heat storage (SHS)** consists of increasing or decreasing the temperature of a certain medium. Unfairly known as the technology with the lowest stored energy density, the higher the imposed temperature difference the higher the energy density these systems have, allowing, in most cases, better stored energy density than latent storage systems. To date, SHS systems are the ones most widely used with the highest market penetration. **Current commercial systems** of the type are those with:

Water as storage medium in a single tank and storing and providing temperatures below 100ºC, so that the most used applications are domestic hot water, district heating (Pit Thermal Energy Storage, PTES,[40]) and low temperature industrial processes (for example, breweries and food industry).

Ceramic bricks as storage medium, both for low temperature applications in domestic storage heaters charged at night-time, and for high temperature applications (> 600ºC) in regenerators for industrial processes (for example, in the glass manufacturing)

Solar salt (nitrates non-eutectic mixture) in two-tank configuration and storing/providing temperatures in the range of 300ºC to 600ºC, so the main application is for power generation with Rankine cycles. These commercial systems can be found in CSTP plants. With an investment cost[41] in 2020 in the range of 20-55 €/kW$_e$h and stored capacities up to 2GW$_e$h, these systems have been identified as a very good large capacity storage approach for PV, as hybrid PV-CSP plants show[42] .

There are several **developments** under study, like those related to the use of other storage media (special concrete formulations, new molten salt mixtures for higher or lower temperatures ranges than solar salt, natural stones, mainly of volcanic nature, glass and steel slags from industrial material waste, etc.) or to explore other system configurations (thermocline tanks where liquid and solid shared the storing of energy, packed beds where the heat transfer area between the solid and the gaseous heat transfer fluid is enhanced by having solid particles, multiple storage tanks configuration, etc.).

In **Latent heat storage (LHS)** the storage medium, known as phase change material (PCM), undergoes a change of physical phase, usually between solid and liquid. The energy density of these systems depends on the phase change enthalpy of the PCM and ranges from 50 kJ/kg upto 2580 kJ/kg with LiH, having a quite

[40] Yutong Xiang, Zichan Xie, Simon Furbo, Dengjia Wang, Meng Gao, Jianhua Fan, A comprehensive review on pit thermal energy storage: Technical elements, numerical approaches and recent applications, Journal of Energy Storage, 55, Part C, 2022, 105716, https://doi.org/10.1016/j.est.2022.105716.

[41] L. Crespo, April 2020, The double role of CSP plants on the future Electrical Systems, presented in the WBG Conference 'Concentrating Solar for Power and Heat'

[42] Noor Energy 1 project in Dubai : 700 MW of CSP + 250 MW of PV + 15 hours of storage at nominal power (Accessed on 24/06/2024; https://www.solarpaces.org/100-mw-csp-tower-operating-in-700-mw-dewa-project-in-dubai/). There are, at least, 7 CSP+PV+ storage under construction in China.

common value of 100-200 kJ/kg. Since the phase transition occurs at nearly constant temperature, which PCM is the most appropriate for a certain application is determined by the main process temperature. Therefore, the most common materials considered for low temperature (<150ºC) are fatty acids, hydrated salts and organics, while for higher temperatures -for either power generation or industrial processes- are eutectic mixtures of nitrates and metals. Although a wide range of applications has been identified and it is probably the thermal energy storage technology on which most research studies have been carried out, there are few commercial examples available, most of them in relation to PCM providers and manufacturers
[43]

In **Thermo-chemical heat storage, TCS**, the energy is stored and released by driving a chemical reaction whose reversibility can be controlled in the temperature range of the intended application. In this case the storage capacity depends on the reaction enthalpy, which is most of the times above 1500kJ/kg, giving to this technology the highest stored energy density award. Like LHS, TCS takes place at constant temperature, which may not be the same for charging and discharging. Examples of TCS are water sorption in zeolites and water uptake of hydrated salts, both for low-temperature (< 100ºC) applications (domestic hot water and district heating),or calcium looping, and metallic oxides for high temperature applications (>450 ºC up to 900 °C)

The maturity of SHS as energy storage systems has promoted the appearance of the new concepts known as **Carnot Batteries** and **Pumped Thermal Energy Storage,** in both a SHS is charged by electricity, usually by electrical heaters (Joule effect) or heat pumps. While Carnot batteries is a more general name, pumped thermal energy storage is related to the combination of TES with heat pumps, both for charging and discharging processes.

[43] A. Miliozzi et a., Energy Procedia, 2015, 82, 730–736, ISSN: 1876-6102

3.3 Chemical Energy Storage

Chemical energy storage, encompassing a range of technologies such Power-to-X (P2X), Power-to-Hydrogen (P2H, with fuel cells/electrolyzers, and hydrogen storage), Power-to-Gas (P2G), represents a crucial component in the transition towards a sustainable energy future. These technologies offer promising solutions for capturing excess energy from renewable sources and converting it into chemical forms that can be conveniently stored, transported, and converted back to electricity or used as fuel when needed.

Hydrogen stands out as a versatile energy carrier in chemical storage. It is primarily produced through electrolysis, a process where electric current splits water into hydrogen and oxygen. This green hydrogen, when generated using electricity from renewable sources like wind or solar, is a zero-carbon fuel. Once produced, hydrogen can be stored in gas or liquid form and transported to where it's needed, or converted directly back into electricity using fuel cells. Fuel cells, particularly proton exchange membrane (PEM) fuel cells, offer efficient conversion of hydrogen back to electricity and are increasingly used in both stationary applications, like power generation for buildings and grid support, and mobile applications, such as in vehicles and drones.

The concept of **Power-to-X** encompasses several pathways, including P2H and P2G, where excess renewable energy is converted into hydrogen (P2H) or further into other gases like methane (P2G) through processes like methanation. P2X also extends to the synthesis of more complex chemicals and fuels, including liquid hydrocarbons, alcohols, ethers or ammonia. These synthesized products can be used in conventional fuel infrastructure and have higher energy densities suitable for heavy transport and industrial processes, making them integral to sectors hard to decarbonize through direct electrification.

Electrolysers, the devices that facilitate the electrolysis process, are pivotal in this energy conversion chain. There are several types of electrolysers, including alkaline, PEM, and solid oxide, each with specific characteristics that make them suitable for different applications based on efficiency, operating temperature, and dynamic response to changing loads. The efficiency of these devices has seen significant improvements, reducing both the capital and operational costs of hydrogen production.

Storage of these fuels poses its own challenges and innovations. Hydrogen can be compressed and stored in tanks or through materials-based solutions such as metal hydrides or liquid organic hydrogen carriers (LOHC). These storage methods cater to different needs concerning volume, safety, and energy density. Similarly, the storage of synthesized fuels requires infrastructure compatible with their chemical nature and use cases.

The integration of chemical energy storage into the energy system also requires consideration of various infrastructural and regulatory aspects. Infrastructure for transportation and distribution, particularly for hydrogen and other gases, needs to be developed or adapted, while safety and regulatory frameworks are essential to facilitate widespread adoption.

Chemical energy storage technologies provide flexibility in energy supply and enable decarbonization of the energy and transport sectors. As the technologies mature and costs continue to decrease, the role of chemical energy storage, from hydrogen to broader P2X applications, can become increasingly central in achieving a resilient and sustainable energy future.

Further on, it must be remarked that these routes besides the production of fuels can be applied for new renewable synthesis routes in chemistry. Ethylene and propylene can be formed by thermo-chemical and electro-chemical devices. Nevertheless, methanol and dimethyl ether are highly important bulk chemicals for further down-stream synthesis processes.

3.4 Mechanical Energy Storage

Mechanical energy storage systems, including technologies such as pumped hydro storage, compressed air energy storage (CAES), liquid air energy storage (LAES), flywheels, and gravitational storage, are vital for enhancing grid stability, balancing supply and demand, and integrating renewable energy sources. These systems store energy in mechanical forms, such as potential or kinetic energy, and can be rapidly deployed to release the energy when needed, helping to manage frequency and provide backup power.

Pumped hydro storage is the most established and widely used form of mechanical energy storage, representing around 90 percent of all grid-connected storage. It involves pumping water from a lower reservoir to an upper reservoir when excess power is available, typically during periods of low demand or high renewable production. The stored energy is recovered by allowing the water to flow back down through turbines, generating electricity. This system is highly effective for load balancing over daily or weekly cycles and offers substantial energy capacity and discharge duration (54 GW in Europe).

Compressed air energy storage (CAES) operates on a similar principle but uses air as the storage medium. Air is compressed and stored under pressure in underground caverns or containers when energy supply exceeds demand. The compressed air is then released to drive turbines and generate electricity when needed. Advances in this technology include adiabatic and isothermal processes, which significantly improve energy efficiency by managing the heat generated during air compression and expansion.

Liquid air energy storage (LAES) or cryegenic energy storage is similar to CAES, but operates on are liquifying the air to be storage in pressurized containers.

Flywheel energy storage systems store energy in the rotational motion of a spinning mass or rotor. The kinetic energy of the flywheel increases as it spins faster and can be converted back to electrical energy through a generator. Flywheels are particularly useful for applications requiring high power, short duration energy bursts, such as frequency regulation and smoothing the output of intermittent renewable sources like wind and solar.

A newer entry to this field is **gravitational energy storage**, which typically involves lifting massive weights in a vertical shaft or along an inclined plane. The potential energy stored in the elevated mass can be recovered by allowing it to descend and drive a generator. This technology promises to provide scalable storage capacity with low environmental impact and high round-trip efficiency.

The advantages of mechanical energy storage are numerous. These systems are generally environmentally friendly, offering clean, non-polluting energy storage solutions. They are also durable, with long lifespans and relatively low maintenance requirements, making them cost-effective over their operational life. Moreover, mechanical storage technologies can be deployed almost anywhere, depending on the geographical and physical constraints of the site.

However, challenges remain, particularly in terms of the geographical limitations associated with technologies like pumped hydro, which requires specific topographical conditions to be viable. For CAES, the availability of suitable geological formations can be a limiting factor, whereas flywheels and gravitational systems face challenges in terms of materials and engineering solutions to ensure safety and efficiency at larger scales. Gravitational energy storage needs big masses or heights, with a need for space, limiting its use in populated areas.

3.5 Superconducting Magnetic Energy Storage

Superconducting Magnetic Energy Storage (SMES) systems offer a highly efficient method for storing electrical energy in the magnetic field created by the flow of direct current in a superconducting coil, which has practically zero resistance. This cutting-edge technology is particularly valued for its rapid response times and high efficiency, making it ideal for applications that require quick energy discharge, such as power quality control, grid stabilization, and bridging power during short interruptions.

The core of a SMES system is its superconducting coil, typically made from materials that can conduct electricity without resistance at very low temperatures. These coils are cooled to cryogenic temperatures using liquid helium or nitrogen, allowing them to maintain a superconducting state. Energy is stored magnetically by circulating a direct current through the coil, and it can be released back into the grid by reversing the current flow.

One of the main advantages of SMES systems is their ability to release stored energy almost instantaneously with very high efficiencies, typically ranging from 95% to 98%. This rapid discharge capability is crucial for applications requiring immediate response, such as stabilizing the electrical grid against fluctuations in demand or supply, particularly those caused by the intermittent nature of renewable energy sources like wind and solar.

Furthermore, SMES units are capable of countless cycles of energy charge and discharge without degradation, which significantly extends their operational lifespan compared to chemical batteries. Their maintenance requirements are also relatively low, contributing further to their long-term cost-effectiveness and reliability.

However, the widespread adoption of SMES technology faces significant challenges. The cost of superconducting materials and the need for cryogenic cooling systems make SMES systems more expensive than other energy storage technologies. The physical size of the systems, driven by the need for large coils to store substantial amounts of energy, also imposes limits on where they can be feasibly deployed.

Research in the field of superconductivity is focusing on developing materials that can operate at higher temperatures (high-temperature superconductors), which could reduce the reliance on expensive and complex cryogenic technology. Advancements in this area have the potential to lower costs and expand the practical applications of SMES.

In terms of applications, SMES systems are particularly suited for short-term energy storage. They are used in facilities that require a high level of power quality and reliability, such as hospitals, military bases, and scientific research facilities. Additionally, they can be integrated into renewable energy installations to smooth out the output and enhance grid stability.

SMES represents a high-performance solution in the spectrum of energy storage technologies, especially for applications requiring quick energy turnaround and high efficiency. As material science advances and costs potentially decrease, SMES could see broader application across more sectors, contributing significantly to grid resilience and the effective integration of renewable energy sources. This technology underscores a crucial intersection of advanced materials science and energy management, reflecting a key component of the future energy landscape.

4. Hybridisation of Energy storage

Introduction to Hybridisation Concepts

Hybridisation broadly refers to combining different components or technologies to form a more capable and resilient system. Within energy storage, hybridisation integrates distinct energy generation, storage, and conversion systems, either physically or through shared control architectures, to achieve greater flexibility, performance, and sustainability than single technologies can deliver alone.

Hybrid Energy Storage Systems exemplify this approach. By combining technologies with complementary characteristics, such as high power density, long discharge duration, rapid response, or low degradation, HESSs can effectively serve multiple energy system needs simultaneously. These systems are increasingly recognised as key enablers of Europe's energy transition, supporting decarbonisation, system resilience, and cross-sector integration.

Figure 4 provides a conceptual overview of the broad technological landscape within which hybridisation strategies are emerging. It highlights how hybrid energy systems can span across generation, storage, conversion, and application domains, offering numerous pathways for integration. As highligheted by the DOE[44], *"one key trend in the evolving U.S. energy sector is the emergence of hybrid energy systems (HES),"* which combine multiple

Hybridisation of energy storage refers to the utilisation of two or more energy storage technologies together on either a system, device, or material level. The hybridised solution should provide technical, economic, reliability, or sustainability advantages beyond what any single energy storage technology can provide over its lifetime.

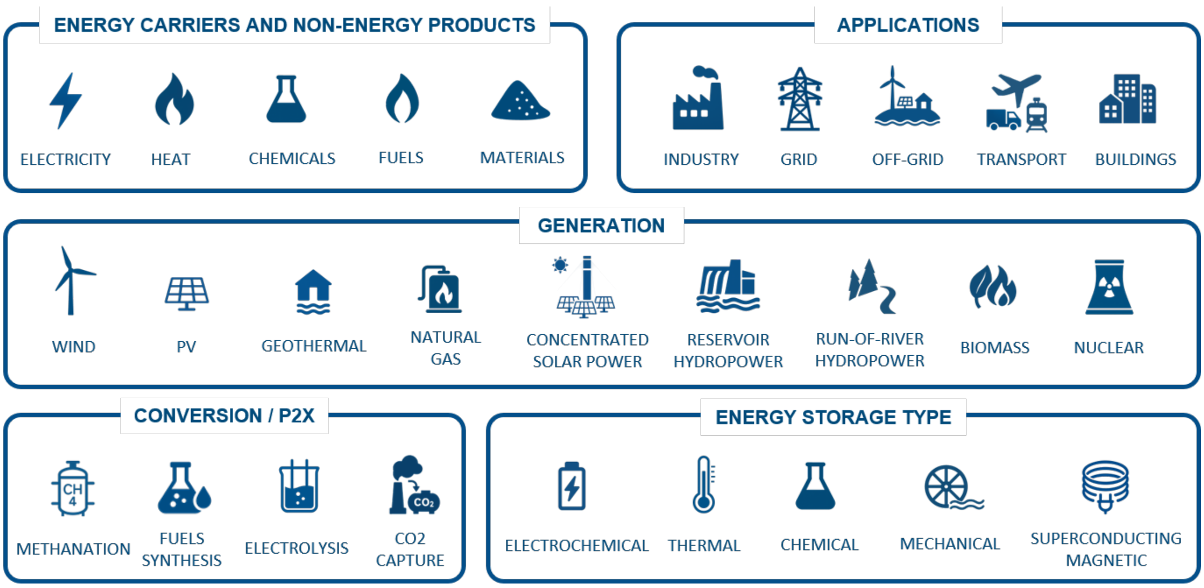


Figure 4. conceptual overview of the broad technological landscape within which hybridisation strategies are emerging

[44] U.S. Department of Energy (DOE). 2021. Hybrid Energy Systems: Opportunities for Coordinated Research. Golden, CO: National Renewable Energy Laboratory. DOE/GO-102021-5447. https://www.nrel.gov/docs/fy21osti/77503.pdf.

generation, storage, and/or conversion technologies to achieve greater value, efficiency, and environmental performance. *These systems offer the opportunity to optimize designs to maximize services that are useful to and valued by the electric and broader energy systems.* In the context of this roadmap, the focus is narrowed to **hybrid energy storage**, encompassing **electrochemical, chemical, thermal, mechanical, and magnetic superconducting** storage technologies.

Dimensions and Levels of Hybridisation

Hybrid energy storage systems can be implemented at different levels depending on how technologies are combined, coordinated, or interconnected. While these levels often overlap, they offer a useful framework for understanding system complexity and integration depth.

Hybridisation can occur at various levels:

- At the **material level**, when a shared carrier or material (e.g., hydrogen, ammonia, or phase-change media) is used across multiple storage or conversion technologies. This promotes sector coupling, circularity, and energy carrier flexibility.
- At the **device level**, multiple storage technologies are combined and integrated within the same hardware assembly, such as in battery-supercapacitor modules or hybrid battery packs.
- At the **system level**, multiple storage technologies operate within the same grid or control environment. Examples include separate thermal and battery storage units serving a microgrid or industrial park, possibly under different operators.
- At the **integrated system level**, technologies are not just co-located but operate under a unified control system and are dispatched as a single hybrid unit. Examples include battery-fuel cell combinations or electrochemical-mechanical pairings controlled by a shared EMS.

In addition to the integration level, the **mechanism of hybridisation** further defines how tightly coupled systems are:

- **Hard-wired Integration**. Direct physical or hardware interconnection of devices, often sharing converters or thermal loops. Common in device-level or material-level hybrids.
- **Soft-wired Integration**. Shared power electronics, conversion infrastructure, or indirect coupling via common electrical buses or pipelines.
- **Software Integration**. Coordination through a supervisory Energy Management System (EMS), even when physical systems are separated. Enables dispatch as a virtual hybrid system.

While these categories offer a typology for design and deployment, real-world systems often blur the lines between them. For example, two storage devices might be independently connected but controlled as one, raising the question of whether they fall under system-level or integrated hybridisation. This highlights the importance of focusing on the **functional goal of hybridisation**, solving a specific energy challenge, rather than fitting neatly into one predefined category.

Functional Advantages of HESS

HESSs enable technologies to operate within their optimal design parameters. High-energy-density systems handle sustained loads, while high-power-density devices manage rapid transients. This complementarity improves overall efficiency, reduces component degradation, and extends system lifespan. One of the defining benefits is **service stacking**: a single hybrid system can provide frequency response, peak shaving, black-start capability, and more: services that traditionally require multiple separate assets. By monetizing these layers of functionality, HESSs improve the cost-effectiveness and ROI of energy storage investments. HESSs can also enhance **resilience**. In critical infrastructure or industrial environments, hybrid systems offer redundancy and flexibility to respond to outages, grid fluctuations, or cyber-physical risks. They can bridge short-term disruptions while supporting longer-term energy delivery.

Opportunities for Service Stacking and Sector Coupling. A major advantage of hybridisation lies in its ability to provide services across different timescales, from milliseconds to days, and physical energy domains, providing:

- Fast-response grid services (e.g., frequency and inertia)
- Mid-term energy shifting (e.g., intra-day balancing)
- Long-duration support (e.g., seasonal energy bridging through chemical or thermal storage)

This multiscale performance is essential as grid flexibility becomes a premium resource. For instance, in power systems with high shares of variable renewables, one hybrid system may offer frequency regulation, inertia emulation, and time-shifted dispatch of stored energy, functions that would otherwise require separate assets.

Hybrid systems also facilitate sector coupling. Electricity can be converted to heat (e.g., via resistive or heat pump storage), to gas (e.g., via electrolysis to hydrogen), or to synthetic fuels or chemicals, enabling integration between electricity, heating and cooling, mobility, and industrial sectors. This versatility supports energy efficiency, curtailment reduction, and decarbonisation in traditionally hard-to-abate sectors.

Hybrid Topologies and Integration Strategies

The structure of a hybrid system strongly influences its performance and adaptability. In a series hybrid configuration, energy flows sequentially through each component, with each stage shaping the final output. Parallel systems distribute the load between technologies operating simultaneously and independently. Buffered configurations use one technology—often with fast response capabilities—as an intermediary to smooth or condition the output of another.

The degree of integration also varies. Some systems are hard-wired at the component level, others rely on shared conversion or control systems, and still others function through software orchestration without physical interconnection. Each model brings different trade-offs in complexity, interoperability, and cost.

System Modularity and Application-Specific Design

The flexibility and scalability of hybrid systems allow them to be tailored for applications ranging from residential microgrids to utility-scale storage or industrial hubs. For instance, integrating thermal and electrochemical storage in a district energy system can stabilise demand peaks, reduce fossil fuel reliance, and improve energy efficiency. In transport, battery-fuel cell hybrids extend range and reduce load on individual systems.

Importantly, hybridisation is not an end in itself but a strategy to solve specific technical and economic challenges. A successful system depends on the right combination of technologies, adapted to its use case, operational conditions, and performance targets.

Application-Specific Optimisation and Metrics

The design and optimisation of hybrid systems must consider technical and operational KPIs such as discharge duration, ramp rates, C-rates, round-trip efficiency, environmental resilience, and lifecycle impacts. These parameters vary significantly across sectors—whether for grid services, industrial processes, building energy management, or transport.

Choosing the right HESS configuration requires evaluating these KPIs in light of the specific demands of each application. For instance, seasonal thermal-electric hybrids in district heating systems will prioritise energy retention and low-cost scalability, while fast-response hybrid battery systems in smart grids will focus on power density, control speed, and communication protocols. In Section 7, we define key performance indicators (KPIs) for HESSs across different sectors. These metrics will inform both design optimisation and policy support.

The following section explores real-world case studies where HESSs have been deployed, piloted, or simply drafted. These examples illustrate how hybrid storage solutions are being tailored to sector-specific needs to meet technical challenges, unlocking economic value, and supporting Europe’s transition to a resilient, zero-carbon energy system, highlighting both opportunities and challenges for broader adoption.

4.1 Case studies for HESS

A number of case studies have been identified and developed to illustrate the application of hybrid energy storage systems across diverse sectors, including **industry**, **grid services**, **off-grid systems**, **transportation**, and **buildings**. These case studies have been compiled with the support of **experts from the StoRIES project** and contribute to the forthcoming book *"Hybrid Energy Storage: Case Studies for the Energy Transition"*, submitted to **Springer Nature**. Additional contributions were provided by the top-performing student team from the **StoRIES Summer School** held in **Rome, June 2024**.

Each case is presented in a consistent **card format**, structured to highlight the:

- **Application** (e.g., electrification, decarbonization, flexibility enhancement),
- **Energy carriers** involved (electricity, heat, fuels, chemical feedstocks),
- **Storage types**, classified as:
  - **EES** – Electrical Energy Storage (e.g., batteries),
  - **TES** – Thermal Energy Storage (e.g., sensible, latent, or thermochemical),
  - **CES** – Chemical Energy Storage (e.g., hydrogen, redox systems),
  - **MES** – Mechanical Energy Storage (e.g., gravity, flywheels),
  - **SMES** – Superconducting Magnetic Energy Storage,
- **Setting and integration approach**, outlining how storage is deployed alongside renewable generation, industrial processes, or infrastructure,
- **Deployment status** (installed, simulated, prototyped, or conceptual),
- **Project location** or context
- **Key benefits** regarding cost savings, emissions reductions, system resilience, and operational flexibility.

Industry. This first group of case studies explores the deployment of hybrid energy storage systems in industrial contexts. Key pathways examined include the **decarbonization of hard-to-abate sectors** such as cement production, the **repurposing of legacy fossil-fuel infrastructure** like coal power plants, and the **optimization of energy flows** within **industrial parks and district heating systems**. These applications include hybrid storage systems to integrate **variable renewable energy sources, recover and reuse waste heat**, and **improve energy cost efficiency** at scale.

The case studies demonstrate how hybrid systems can be tailored to industrial needs by combining storage technologies such as batteries, molten salt tanks, thermochemical reactors, and flywheels, each playing a distinct role in balancing energy supply and demand. Across different technology readiness levels and deployment contexts, from installed demonstrators to simulated future configurations, these examples provide insights into how hybrid storage can underpin a flexible, low-carbon, and economically competitive industrial energy transition.

High-Temperature Heat & Electricity Storage for Industry	
Application	Decarbonization and energy cost reduction in industrial parks and district heating systems through integrated thermal and electrical storage.
Energy Carriers	Heat, electricity
Storage Type	EES (Batteries) + TES (Sensible Heat Storage + Latent Heat Storage + Thermochemical Storage).
Setting & Integration	Multi-energy industrial parks and district heating; integrated operation of CHP, PV, batteries, heat pumps, and TES; real-world optimization using Iberian and UK market data (Manchester Microgrid).
Status	Installed and demonstrated + real-case simulations.
Project / Location	Industrial Park Demonstration + Manchester University Microgrid (UK).
Benefits	Cost optimization (up to 28% energy cost reduction vs single-energy setups). Enhanced market participation (electricity, gas, CO_2, secondary reserve). Renewable integration and overproduction absorption. Grid stability and multi-energy system resilience. Coordinated dispatch improves overall system efficiency.

[45]

Hard-to-Abate Industry Decarbonization	
Application	Deep decarbonization of cement production through electrification, renewables, and integrated energy storage.
Energy Carriers	Heat, electricity, fuels
Storage Type	EES (Sodium-ion Batteries) + CES (Reversible Molten Carbonate Fuel Cells).
Setting & Integration	Electrified kilns powered by on-site renewables, thermal recovery, and CO_2 capture systems; grid-connected and hybrid configurations across European climates.
Status	Drafted + simulated
Project / Location	Electrified Cement Plant Demonstration (3 EU sites).
Benefits	CO_2 emissions reduction (45–47% across case studies). Fossil-free high-temperature heat supply. Competitive energy cost (LCOE: $247–285/MWh). Scalability across diverse climates and industrial contexts. Integrated CO_2 capture improves sustainability and system efficiency

[46]

[45] Scipioni R., Gil Bardají M.E., Barelli L., Baumann M., Passerini S., (Eds.) (2025). *Hybrid Energy Storage: Case studies for the energy transition* [in press]. Springer.

[46] Ahmadi N., Das S., Delawary A., Mataloni S., Richter L., Salmelin M., Santa Maria J., Smith J., Passerini S., Scipioni R., (2025). *Decarbonizing Hard-to-Abate Sectors: a Hybrid Electrification approach for Low-Carbon Cement Production.* Manuscript submitted for publication.

Repurposing retired fossil plants

Application	Transforming decommissioned coal plants into sustainable energy hubs through hybrid energy storage and renewable integration.
Energy Carriers	Heat, electricity
Storage Type	TES (Molten Salt) + EES (Second-Life Batteries) + MES (Flywheels).
Setting & Integration	Existing coal infrastructure retrofitted into Thermal Storage Power Plants (TSPP); centralized control and hybrid dispatch with renewable generation.
Status	Simulated
Project / Location	Thermal Storage Power Plant (TSPP) Concept
Benefits	Cost optimization (second-life batteries and thermal storage reduce long-term costs). System resilience (hybrid configuration enhances flexibility and redundancy). Temporal complementarity (flywheels stabilize millisecond-scale fluctuations, batteries cover mid-term, TES provides long-duration backup). Emissions reduction and reuse of existing assets.

Renewable Power Systems Smoothing

Application	Optimizing hybrid renewable systems using gravity energy storage and batteries to balance intermittent wind and solar generation
Energy Carriers	Electricity
Storage Type	EES (High-power batteries) + Mechanical Energy Storage (Gravity Energy Storage).
Setting & Integration	Renewable microgrids combining PV and wind generation with AI-based sizing and control (Fmincon optimization); adaptable to grid-connected or off-grid settings.
Status	Simulated and optimized.
Project / Location	PV/Wind + Gravity-Battery Optimization Study
Benefits	Enhanced system reliability and dispatchability. Cost-effective delivery (COE: 0.09–0.22 €/kWh depending on reliability level). Complementary operation (GES for long-duration, batteries for fast response). Improved renewable energy utilization. Optimization ensures lifecycle cost minimization at target performance.

GRID. This group of case studies focuses on the role of hybrid energy storage systems in **enhancing grid reliability, stability, and flexibility**. These systems are designed to address critical needs in power networks, such as **frequency regulation**, **voltage support**, **power smoothing**, and **integration of variable renewable energy sources**. By combining different storage technologies with complementary response times and storage durations—such as **supercapacitors**, **lithium-ion batteries**, **superconducting magnetic storage**, and **flywheels**—hybrid systems deliver **real-time grid services** and help reduce stress on existing infrastructure.

The case studies presented here cover a range of grid contexts, from **substation-level hybrid storage** to **hydropower plant upgrades** and **wind/solar integration**. These projects, at both **laboratory validation** and **simulation stages**, demonstrate how intelligent control strategies (e.g., fuzzy logic, moving average filtering, high-level dispatch coordination) can optimize power sharing, reduce wear on storage components, and enable participation in **ancillary service markets**. These configurations offer promising pathways for **extending asset lifetimes**, **minimizing operational costs**, and **maintaining power quality** in increasingly dynamic and decentralized energy systems.

Equipment lifetime extension, ancillary services	
Application	Enhancing frequency regulation in hydro plants and reducing mechanical stress through energy storage integration.
Energy Carriers	Electricity
Storage Type	EES (Li-ion Batteries) + EES (Supercapacitors)
Setting & Integration	Run-of-river, pumped-storage, or reservoir hydro coordinated with short- and medium-duration storage. Validated via lab-scale hardware-in-the-loop systems.
Status	Lab-tested + hardware-in-the-loop.
Project / Location	Hybrid Hydro System (CIEMAT Lab)
Benefits	Regulation enhancement (faster and finer grid frequency response). Component protection (reduced hydro mechanical wear and battery cycling). Extended lifespan. Market access for ancillary services. Environmental performance (stabilized river flow and reduced ramping).

Voltage and Frequency Support	
Application	Providing grid support services with rapid-response and long-duration energy storage systems.
Energy Carriers	Electricity
Storage Type	EES (Li-ion Batteries) + EES (Supercapacitors or Superconducting Magnetic Energy Storage).
Setting & Integration	Substation-level HESS (10/0.4 kV) with AI-based control (Fuzzy Logic + Moving Average) using real load profiles from southern Germany.
Status	Simulated
Project / Location	Simulated grid-connected HESS using southern Germany load data
Benefits	Power quality enhancement. Component protection (battery life extension). Flexible grid services (real-time ramp rate and SoC management). Efficient dispatch under volatile loads. High-resolution operation (1 s control, ±30 kW noise filtering).

Power Smoothing	
Application	Power smoothing and frequency stabilization for wind and solar power plants.
Energy Carriers	Electricity
Storage Type	EES (Li-ion Batteries – LFP/NMC) + MES (Flywheels)
Setting & Integration	Hybrid Energy Storage System (HESS) integrated into the DC bus of wind/solar plants using back-to-back converters; validated in lab and simulated for offshore wind turbines and a 2 MW onshore system in Italy.
Status	Simulated + Lab modeled
Project / Location	Flywheel + Battery Wind Plant Integration (Italy)
Benefits	Grid stability improvement (voltage/power ramp reductions up to 80%). Transient frequency drop mitigation (by 89%). Battery lifespan extension. Economic viability (LCOE: 8.27–9.98 c€/kWh). Participation in fast reserve support markets.

Off-grid. This group of case studies explores the use of hybrid energy storage systems in **remote and off-grid contexts**, where energy autonomy, reliability, and sustainability are essential. Applications include **resilient energy supply for cold-climate communities**, **solar-dominated microgrids in southern regions**, and **renewable energy communities (RECs)** aiming for local energy independence. These systems combine various storage technologies, such as **lithium-ion batteries**, **hydrogen storage**, and **thermal energy storage (TES)**, to match the diverse and fluctuating energy demands typical of off-grid environments.

The case studies highlight real-world deployments in Norway and Gran Canaria under the REMOTE project, as well as simulated optimization in REC scenarios. They demonstrate how **thermal storage and heat pumps** can increase efficiency and reduce emissions, while **hydrogen systems** provide long-duration backup in the absence of solar input. Optimization tools are also used to assess performance and cost-effectiveness across different storage mixes. These configurations are particularly effective in **minimizing diesel use**, **lowering the Levelized Cost of Energy (LCOE)**, and **boosting energy self-sufficiency**, making hybrid storage a robust solution for off-grid sustainability transitions.

Cold-Climate Resilience	
Application	Resilient off-grid power and heating supply for remote communities in cold climates.
Energy Carriers	Electricity, fuels, heat
Storage Type	EES (Li-ion Batteries) + CES (Hydrogen) + TES (Thermal Storage with Heat Pumps).
Setting & Integration	Remote dairy farm in Rye, Norway (REMOTE project); integrated PV, wind, and hydrogen-based system with TES and advanced control for autonomous, year-round operation.
Status	EES/CES system installed. Extended version (with TES) conceptualized and simulated.
Project / Location	REMOTE Project – Rye, Norway
Benefits	Enhanced energy resilience in winter. TES and heat pumps reduce PV curtailment (from 38% to 19%). Emissions reduced to 16,952 kg CO_2-eq/year. Net Present Cost cut by over 40% (€1.03M to €604k). LCOE/LCOS reduced to €0.45/kWh with balanced hybrid design.

Southern Microgrids

Application	Autonomous microgrid operation and PV integration in sunny, off-grid locations.
Energy Carriers	Electricity, fuels
Storage Type	EES (Li-ion Batteries) + CES (Hydrogen: Electrolyzer + Tank + Fuel Cell)
Setting & Integration	Demonstrator at a cattle farm in Gran Canaria (REMOTE project); hybrid storage manages solar intermittency and reduces reliance on fossil gensets.
Status	Installed
Project / Location	REMOTE Project – Gran Canaria, Spain
Benefits	Emissions reduced by 50% vs diesel reference. LCOE improved from €0.57 to €0.39/kWh. LCOS lowered from €1.5 to €0.59/kWh with optimized scheduling. Higher PV penetration and reduced genset dependency through hybrid control.

Renewable Energy Communities

Application	Evaluation and optimization of energy storage systems for local energy sharing and self-sufficiency in RECs.
Energy Carriers	Electricity, heat
Storage Type	EES (Li-ion Batteries) + TES (Phase Change Material Modules)
Setting & Integration	Simulated REC with flexible storage sizing; scenarios tested under self-sufficiency and economic objectives
Status	Simulated + benchmarking tool implemented
Project / Location	StoRIES, Reference Benchmark Tool
Benefits	Stable LCOE around €0.097–0.098/kWh across all configurations. CO_2 reduction up to 0.45 kg/kWh (Scenario 1). System efficiency up to 98% (Scenario 3). Balanced trade-offs between CAPEX, performance, and emissions.

Transport. Hybrid energy storage systems are emerging as **key enablers of low-emission transport solutions** across multiple modes of mobility, including road, rail, maritime, and aviation. This group of case studies illustrates how combining **electrical (batteries), chemical (hydrogen, aluminum), and advanced storage materials** supports the shift away from fossil fuels in both passenger and freight sectors.

The selected examples span from **urban electric buses** and **hydrogen-powered regional trains** to **zero-emission maritime vessels** and **next-generation electric aircraft**. In addition, innovative systems for **EV and FCEV charging infrastructure**, such as those using aluminum energy carriers, demonstrate the versatility of hybrid storage concepts. Each solution addresses specific transport challenges, such as **range extension**, **fuel cost reduction**, **recharge/refueling time minimization**, and **infrastructure flexibility**.

The cases vary in technological maturity, from **real-world simulations** and **ongoing demonstrations** to **conceptual system designs** and showcase how hybrid storage can meet demanding operational profiles while enabling long-term decarbonization in the transport sector.

EV Charging & Hydrogen Refuelling	
Application	Supporting battery electric vehicle (BEV) charging and fuel cell electric vehicle (FCEV) hydrogen refueling with aluminum-based energy systems.
Energy Carriers	Electricity, fuels, chemicals
Storage Type	EES (Battery) + CES (Solid-Oxide Fuel Cells) + Chemical Storage (Aluminum energy carrier).
Setting & Integration	Conceptual 3.9 MW hybrid EV/FCEV charging station with aluminum wet-combustion, SOFCs, and heat recovery; designed for grid or off-grid applications.
Status	Conceptual / idealized
Project / Location	Aluminum Energy Carrier Study (Ersoy et al.)
Benefits	Dual-purpose energy carrier for electricity and H_2. Grid stress mitigation and energy resilience. Circular aluminum use reduces lifecycle impacts. Scalable and modular for future mobility hubs. LCOE: €152–334/MWh. LCOH: €5.4–11.8/kg.

Maritime & Port Electrification	
Application	Decarbonizing port equipment and maritime transport through hybrid battery-fuel cell systems.
Energy Carriers	Electricity, fuels
Storage Type	EES (Lithium-ion Batteries) + CES (Hydrogen Fuel Cells)
Setting & Integration	RTG cranes, tugs, drayage trucks, and ferries (e.g., HySeas III) using shore power, onboard storage, and battery swapping; integrated with wind-powered H_2 and emerging port standards.
Status	Simulated + emerging demonstrations
Project / Location	HySeas III, MF Hydra (Norway), Sea Change (USA).
Benefits	GHG emissions reduction (up to 80.4%). Fuel savings (up to 40%). Zero-emission ferry operation. Flexible refueling options and modular deployment. Lifecycle emissions reduced (from 27.0 to 5.3 kg CO_2eq/km).

Rail Transport Electrification	
Application	Decarbonizing non-electrified railway lines with hybrid hydrogen and battery propulsion systems.
Energy Carriers	Electricity, fuels
Storage Type	EES (Battery Energy Storage Systems) + CES (Hydrogen Fuel Cells).
Setting & Integration	Regional and intercity rail lines in Italy, Germany, and the UK where full electrification is impractical
Status	Drafted + evaluated via MCDA tool (Multi-Criteria Decision Analysis)
Project / Location	Hydrogen + Battery Trains (EU); TRL emerging
Benefits	Local emission elimination (up to 100% on non-electrified lines). Lifecycle GHG reduction (from 27 to 5.3 kg CO_2eq/km). High operational flexibility and route adaptability. Balanced investment planning using structured MCDA

Aviation Electrification	
Application	Reducing emissions in commuter, regional, and short-to-medium range aircraft through electrification and hybrid battery systems.
Energy Carriers	Electricity
Storage Type	EES (High-energy-density Li-ion Batteries + Experimental Structural Battery Composites).
Setting & Integration	Applied in hybrid-electric and more-electric aircraft (e.g., ES-30, ATR-EVO); studied in EU research projects (HERA, HECATE, SOLIFLY, MATISSE); future integration into non-safety-critical aircraft structures.
Status	Drafted + prototype stage
Project / Location	HERA, HECATE, SOLIFLY, MATISSE
Benefits	Aviation-wide emissions reduction (3–3.5%). Up to 40% GHG reduction in commuter and regional segments. Structural batteries could add 0.6–1.8 MWh hidden capacity. Lightweight integration with future energy density targets up to 1 kWh/kg

Heavy-Duty Transport – Urban Electric Bus

Application	Enhancing electric bus performance via hybrid energy storage for improved range, lifecycle cost, and battery durability
Energy Carriers	Electricity, fuels
Storage Type	EES (LFP, Vanadium Redox Flow Battery, Ni-NaCl) + CES (PEM Fuel Cells)
Setting & Integration	Simulated over 365-day urban drive cycles in Italy; tested across four hybrid configurations (LFP/PEMFC, LFP-only, LFP/VRFB, Ni-NaCl/PEMFC).
Status	Simulated using real-world load profiles
Project / Location	Urban Electric Bus Study (Italy)
Benefits	Battery lifespan increased up to 9.5 years in hybrid VRFB setup vs 1.8 years for standalone LFP. Reduced recharge time (~80 min vs >2 h). Extended range and improved DoD profiles. Lifecycle cost savings via reduced battery replacements.

Buildings. Hybrid energy storage systems are increasingly important in the **decarbonization and optimization of building energy systems**, supporting both **residential and commercial** users in achieving energy self-sufficiency, flexibility, and resilience. The following case studies illustrate how hybrid storage—combining **electrical, thermal, and advanced flow battery technologies**—can enable **smart energy management**, especially when integrated with **on-site solar production** and **heat pump systems**.

Applications range from **single-family homes** and **office buildings** to **community-scale systems**, each leveraging a tailored combination of **battery energy storage (EES)** and **thermal energy storage (TES)** to manage variable demand across heating, cooling, domestic hot water, and electricity. The **HYBUILD demonstrator** shows the feasibility of combining **PCM, thermochemical storage, and lithium-ion batteries** in a real Mediterranean climate, while the **Trondheim office study** applies monthly-optimized storage sizing to reduce operational costs and emissions. The **HYBRIS project** further demonstrates behind-the-meter hybrid systems that serve multiple services (peak shaving, arbitrage, islanding) and deliver community benefits.

Together, these cases underscore the **role of hybrid storage in supporting energy-positive buildings**, advancing the integration of renewables, and unlocking new business models for distributed energy services.

Smart Buildings – Residential Hybrid Storage

Application	Solar-powered building energy system for combined space heating, cooling, DHW, and electricity management.
Energy Carriers	Electricity, heat
Storage Type	TES (Phase Change Material, Thermochemical, Hot Water Tanks) + EES (Lithium-ion Batteries).
Setting & Integration	Two-floor single-family house in Almatret, Spain; integration of reversible heat pump, sorption chiller, PV, Fresnel solar collectors, and hybrid storage system.
Status	Installed and monitored.
Project / Location	HYBUILD Project – Almatret, Spain.
Benefits	Self-consumption up to 0.80. Self-sufficiency of 0.50. Renewable share up to 0.67. Improved seasonal efficiency. Multi-service coverage (heating, cooling, DHW, electricity). Demonstrated viability in real Mediterranean setting.

Smart Buildings – Office Hybrid Storage Optimization

Application	Energy optimization in net-zero office building with combined thermal and electrical storage.
Energy Carriers	Electricity, heat
Storage Type	EES (Battery Energy Storage System – 67 kWh) + TES (Hot Water Tank + Phase Change Material – 104 kWh)
Setting & Integration	Office building in Trondheim, Norway; monthly-optimized hybrid storage based on energy price and seasonal thermal demand using convex optimization.
Status	TES system installed. Hybrid (with EES), simulated and optimized.
Project / Location	ZEB Lab – Trondheim
Benefits	Cost-efficient hybrid sizing tailored to local energy price fluctuations. Seasonal performance balance with higher TES use in winter. Lower CO_2 footprint for TES (especially with PCM). Improved system flexibility via heat pump + BESS interaction. Location-specific optimization enhances replicability.

Behind-the-Meter Storage – Community and Commercial Energy Services

Application	Multi-service behind-the-meter energy management for communities, business parks, and industrial users.
Energy Carriers	Electricity
Storage Type	EES (Lithium Titanate Batteries + Aqueous Organic Redox Flow Batteries)
Setting & Integration	Real deployment in Messina (Italy); virtual deployment in Belgium and the Netherlands. Containerized system with integrated cloud/local control and digital twin validation.
Status	Installed (Messina, Italy) + Simulated (Belgium, Netherlands).
Project / Location	HYBRIS Project
Benefits	Increased PV self-consumption (>75%). Improved self-sufficiency through night-time energy support. Reliable backup with successful outage avoidance (~40/year). Multi-service delivery: peak shaving, arbitrage, demand/response. Social impact via community energy sharing (≥50 kWh/day). Revenue potential from grid-responsive services

5. Barriers and challenges

Hybrid energy storage systems face a series of complex **technical challenges** that span from improving the underlying technologies and materials to ensuring their seamless integration within the broader power grid. These challenges are not limited to the hybridization of storage technologies but also demand significant advancements in each component technology, innovations in materials, optimization of control systems, and the development of sustainable manufacturing and supply chains. Key factors influencing the cost, reliability, and overall performance of energy storage solutions include scaling up production capacity, enhancing material properties, fostering competitive supply networks, achieving performance improvements, and maximizing the long-term benefits for both industry and end-users.

Moreover, the transition to a low-carbon, renewable-based energy system necessitates that HESS address broader systemic issues, including grid stability, energy management, and environmental sustainability.

These technical challenges are deeply interconnected with **socio-economic aspects** such as market readiness, public acceptance, workforce development, and equitable access to energy technologies. Equally critical are the **legislative and regulatory frameworks** that will govern the deployment, operation, and circular economy integration of energy storage systems across Europe and beyond.

In the following sections, we outline several key challenges anticipated in the coming years. These challenges serve as the foundation for defining **Strategic Research Areas** and corresponding research and innovation priorities, as articulated in the **Strategic Research and Innovation Agenda (SRIA)**. Together, the technical, socio-economic, and legislative dimensions form a comprehensive roadmap to guide the future development and deployment of hybrid energy storage systems.

5.1 Technical challenges

TECHNOLOGICAL MATURITY

Challenge 1. Dimensioning and Optimal Operation: One of the core challenges is the correct dimensioning and definition of optimal operation strategies for energy storage systems:

i. Development of Comprehensive Sizing Methodologies: This includes problem evaluation, technology selection, operational optimization, integration with renewable energy sources, and techno-economic feasibility analysis.
ii. Role in Network Planning: Energy storage must be fully integrated into future grid planning processes.
iii. Incorporation of Artificial Intelligence (AI): AI techniques can optimize the operation of hybrid systems, coordinating various energy storage technologies alongside distributed renewable energy sources.

Challenge 2. Reliability of hybrid Energy Storage Systems: While there are generally safe technologies, failures under extreme conditions pose significant risks. Future efforts should focus on:

i. Enhancing Safety: For components as batteries, incorporating e.g. solid electrolytes or stable electrodes to improve inherent safety[47].
ii. Predictive Safety Diagnostics: Early detection, predictive diagnostics, and aging control mechanisms must be advanced for hybrid system

MATERIALS INNOVATION

Challenge 3. Materials involved in Storage Systems: The durability, efficiency, and sustainability of storage systems heavily depend on the materials used:

i. Development of Novel Materials: New materials should ensure increased efficiency, reduced environmental and social impact, and minimal reliance on critical or scarce raw materials.
ii. Critical Raw Materials Strategy: European initiatives like the Study on Critical Raw Materials for the EU[48] and the Critical Raw Materials Act[49] stress the need for alternative material exploration, European mining and processing capacities, recycling, and securing supply chains.

ENERGY MANAGEMENT SYSTEMS (EMS)

Challenge 4. AI-driven EMS: nowadays, only partial quantities of the diverse data obtained by the energy storage systems are centrally collected. In the coming years, AI will experience huge development in the energy management system field. AI will play a crucial role in analyzing vast datasets from energy storage systems and generation units, optimizing EMS, and preventing generation peaks. Consequently, there will be a huge demand of working force in this field.

Challenge 5. Development of DC Networks To undertake the transition of electricity grids to the smart-grid paradigm, the interconnection of generation and consumption that use or produce DC, such as photovoltaic systems, controlled speed wind turbines, electric mobility, or the

[47] Workshop on Energy Conversion and Storage Days, Karlsruhe, 2023. EnBW

[48] Study on the Critical Raw Materials for the EU 2023 - Publications Office of the European Union.

[49] Critical Raw Materials Act. Challenges and Opportunities Ahead. SUPEERA

majority of knew charges of the industrial and domestic sectors, must be developed. Distribution Network Operators (or Distribution System Operators, DSOs) face increasingly demanding network requirements relating to cost, efficiency, and network quality. In addition, new challenges are appearing, such as the emergence of charger's electric car (EV), the integration of distributed resources (DERs), as well as support for existing demand. DC networks can improve grid operation in terms of providing greater power capacity and voltage controllability. DC solutions can be even cheaper than AC alternatives in certain cases.

For large-scale DC implementation, the following actions and measures are necessary first:

i. Clear use cases and business models must be established by DSOs and service providers.
ii. Regulatory frameworks and standardization guidelines are essential.
iii. Pilot projects involving Distribution System Operators (DSOs) should be increased[50].

GRID STABILITY

The integration of Variable Renewable Energy (VRE) poses challenges to grid stability.

Challenge 6: System robustness & stability enhancement: The European energy system should assure the capacity of electricity generation to cover the peak hour with a huge probability and availability to provide electricity rapidly. However, with the increase of VRE penetration into the electricity grid generation, the robustness of the system is not guaranteed because of the nature of the renewable energy systems.

Introducing different types of energy storage systems (hybridization of them) will certainly support system stability.

The European grid needs to be stronger to compensate for fluctuations of electricity supply and demand. Besides, it is important to highlight that the deployment of the grid is compulsory to reduce the congestion of the transmission of energy between countries. The energy storage solutions and the increased penetration of renewable energy are being deployed before reinforcing the European grid.

Challenge 7. Harmonics and Control Systems: in the field of power electronics, mitigating harmonics from power converters and developing control systems for multi-technology energy storage systems are essential steps. This will be necessary to manage different storage systems at the same time, making possible a good balance of power and energy within the hybrid energy storage system.

Challenge 8. Inertia[51] challenges: the modern power system is progressing from a synchronous machine-based system towards an inverter-dominated system, with large-scale penetration of renewable energy sources. This inverted-dominated system has the problem of reduced inertia that we must solve.

For achieving this challenge, we must face with different solutions such as:

i. Development of energy storage systems and consequently, hybridization of different types of energy storage solutions

[50] Congress of Intelligent Grid, December 2022. Futured

[51] Inertia is described by the European Network of Transmission System Operators for Electricity (ENTSO-E) as "The property of a rotating rigid body, such as the rotor of an alternator, such that it maintains its state of uniform rotational motion and angular momentum unless an external torque is applied'.

ii. Deployment of Virtual inertia (see also challenge 10)[52]

Challenge 9. Grid flexibility: the future electricity system should be provided with a mechanism of flexibility. The increase in VRE into the grid is associated with a reduction of system flexibility since renewable energy systems depend on environmental factors to produce energy.

For instance, in the case of solar FV energy in the domestic sector, the highest electricity production typically occurs when people are not at home, leading to excess generation that often goes unused. On the other hand, during periods of low wind or lack of sunlight, the system may produce insufficient energy to meet demand.[53]

To address these issues and ensure a resilient, reliable, and efficient power grid, enhancing grid flexibility is essential. Flexibility must be introduced across three main areas:

- **Demand Flexibility:** Demand-side flexibility can be achieved through demand response strategies and intelligent consumption management. Large-scale consumers, as well as smaller consumers, can modulate their energy usage during periods of scarcity or peak demand, contributing to grid stability.
- **Generation Flexibility:** Historically, flexibility has been provided by dispatchable, conventional power plants such as combined cycle units, capable of quickly adjusting output to meet varying demand. However, as VRE penetration increases, overgeneration events and rapid fluctuations become more frequent:
    i. Reducing VRE Curtailment: High levels of VRE penetration can lead to curtailment, where the output of renewable units is deliberately reduced to maintain grid balance. Curtailment rates increase as VRE capacity grows, eventually limiting the economic viability of further renewable deployment. Apart of having a energy map based on diverse VRE, hybrid energy storage systems offer a solution by absorbing excess generation and discharging during periods of low production, thus minimizing curtailment[54].
    ii. Decreasing Net Load Ramping: Increased VRE leads to steeper changes in net load, forcing conventional units to cycle more frequently and quickly. Hybrid energy storage systems can smooth out these ramps, providing the necessary buffer to reduce strain on conventional generators[54].
- **Grid Flexibility via Energy Storage Systems:** energy storage systems can store energy in hours of less demand and can supply electricity later, depending on the necessities of the system. Consequently, it is necessary to improve the flexibility of the systems by adding dispatchable technologies and managing the demand of electricity and installing energy storage systems and, of course, the hybridization of energy storages technologies.

Challenge 10. Grid-forming converters, enabling the future grid: Another crucial aspect of future grid flexibility lies in the development of grid-forming converters (GFM). Currently, most renewable power plants are connected via voltage source converters (VSC), which function as grid-

[52] Virtual inertia: Current trends and future directions. *Applied Science*, 2017

[53] Fundación Naturgy: El papel del almacenamiento energético en la transición energética.

[54] IEA – Renewable Energy Market Update, June 2023

following converters. These rely on the existing grid's voltage and frequency to operate and cannot independently establish grid conditions.

In contrast, grid-forming converters can actively create and maintain voltage and frequency, using auto synchronization, effectively establishing a stable grid environment without the need for conventional synchronous generators. As the proportion of conventional generators decreases, GFMs will become essential for:

- Ensuring grid stability and security.
- Facilitating higher integration of renewable energy sources.
- Supporting the autonomous operation of decentralized power systems.

A prime example is Spain's Inertia+ Project, led by Hesstec and funded by Iberdrola Renovables and Red Eléctrica, which demonstrates the potential of hybrid energy storage systems to provide grid-forming capabilities[55].

ENVIRONMENTAL CONSIDERATIONS

Challenge 11. Advancing circular economy strategies for Hybrid Energy Storage Systems: the transition to a sustainable, low-carbon energy system must be accompanied by the development of environmentally responsible energy storage solutions. A key priority is adopting a circular economy approach, guided by the **R-ladder strategy**, which includes: *refuse*, *rethink*, *reduce*, *reuse*, *repair*, *remanufacture*, *repurpose*, *recycle*, and *energy recovery*[56].

- **Reduce, Rethink, and Refuse**

Reducing reliance on critical and scarce raw materials—such as lithium, cobalt, and nickel in batteries—is essential. Strategies should focus on:

i. Minimizing the use of toxic components to prevent environmental contamination.
ii. Designing systems that require fewer critical materials without compromising performance.

Europe's heavy dependence on imported critical raw materials highlights the urgency of:

i. **Upscaling domestic mining**, though community acceptance and environmental safeguards remain significant challenges.
ii. **Increasing recycling capacities** in sectors like batteries, hydrogen, and semiconductors.
iii. **Diversifying supply chains** through global partnerships and stable trade agreements (Critical Raw Materials Act, 2023).

- **Reuse and Second-Life Applications**

Reusing batteries, particularly from electric vehicles, for grid services is a promising strategy to extend product lifespans and reduce raw material demand. However, recycling costs and infrastructure remain barriers. The new **EU Battery Regulation** mandates safer post-consumer battery management and promotes second-life applications[57]. Second-life applications can also apply to other storage technologies and components, such as power electronics, controllers, and cooling systems. However, the feasibility of second-life applications still remains a challenge, as it often depends on standardization, safety assurance, and

[55] Congress of Intelligent Grid, 'Potential of Hybrid Energy Storage Systems for Providing Grid-Forming Capabilities: Inertia+ Project'. Iberdrola, Hesstec, Red Eléctrica.

[56] ETIP PV / EERA: Strategic Research and Innovation Agenda on Photovoltaics

[57] EUR-Lex - 32023R1542 - EN - EUR-Lex (Battery Regulation)

cost-effective refurbishing processes that are not in place yet. The current regulatory framework must be expanded to encompass these broader second-life opportunities, promoting cross-technology reuse within HESS.

- **Repair and Remanufacture**

The supply chain must shift toward greater repairability and remanufacturing. Regulations currently lack incentives for circular product design, but the upcoming EU frameworks aim to address this gap. For instance, the new Battery Regulation requires minimum levels of material recovery (e.g., cobalt 16%, lithium 6%, nickel 6%), supporting remanufacturing efforts[58].

- **Repurpose**

Repurposing existing infrastructure offers significant opportunities to reduce environmental impacts, lower costs, and accelerate the deployment of hybrid energy storage systems. Beyond product-level strategies, system-level repurpose should also be prioritized, including:

i. **Conversion of Decommissioned Fossil Fuel Plants:** retired coal or gas-fired power plants can be repurposed as thermal storage power plants[59] or better, since their capabilities are improved, as hybrid energy storage hubs. Their existing grid connections, substations, and cooling infrastructure can be adapted to host a combination of storage technologies (such as batteries, thermal storage, or flywheels), supporting grid stability and facilitating renewable integration.

ii. **Repurposing Obsolete Storage Systems:** components from outdated or underperforming storage technologies, such as older battery chemistries or power electronics, can be refurbished or combined with new technologies within hybrid systems, extending their useful life.

iii. **Infrastructure Integration:** Repurposing defunct industrial sites, transmission assets, or substations to host hybrid storage systems reduces land use pressures and speeds up project implementation.

- **Recycle and Energy Recovery**

Recycling is crucial to minimize the environmental footprint of storage technologies while ensuring security and reliability. The **Batteries Directive (Directive 2006/66/EC)** obligates producers to finance battery collection and recycling processes, aiming to increase recycling rates and reduce waste[60]. Enhancing Europe's recycling industry and integrating secondary raw materials into production is vital to achieving circularity goals[61].

Any negative impact associated with the life cycle of any energy storage technology and consequently, the hybridization of them, must be minimized. Environmental impacts of energy storage technologies should be determined using the Lifecycle Assessment (LCA). LCA is an ISO standardized method that builds an inventory of all materials and energy that is required to obtain the final product.

It is noteworthy that LCA experts face difficulties gathering the data needed for their studies, because data among different companies is difficult to find and it is not publicly available or the absence of established recycling strategies. It is important that this information could be publicly accessible. On the other hand, LCA

[58] Fundación Naturgy: El papel del almacenamiento energético en la transición energética

[59] Geyer, M., Trieb, F. and Giuliano, S. (2020) Repurposing of existing coal-fired power plants into Thermal Storage Plants for renewable power in Chile. Bonn, Germany.

[60] EUR-Lex - 02006L0066-20180704 - EN - EUR-Lex

[61] Batteries Europe. Research and Innovation Roadmap on Battery Technologies (2023)

softwares are not as flexibles as desired, and it will be necessary to improve and develop them in the next decades.

Challenge 12. Development of ecologically friendly, sustainable, and resilient supply chains: achieving Europe's decarbonization objectives must go hand in hand with the development of sustainable and resilient supply chains for energy storage technologies. Beyond reducing greenhouse gas emissions, it is essential to ensure that the materials and processes used in the manufacturing of energy storage systems are environmentally responsible, resource-efficient, and socially sustainable.

This challenge involves the following key priorities:

- **Innovation in Materials:** Research and development efforts must focus on discovering and adopting new materials that are inherently safer, less toxic, and more environmentally friendly than some of those currently in use.
- **Integration of Secondary Raw Materials:** It is crucial to promote the incorporation of recycled and secondary raw materials, such as recovered lithium, cobalt, nickel, and other critical elements, into the manufacturing processes of batteries and other energy storage components.
- **Expansion of Recycling Capabilities:** Scaling up Europe's recycling infrastructure will be key to reducing dependence on primary raw material imports, decreasing environmental impacts, and supporting the circular economy.

Building a sustainable supply chain will require collaboration between industry, policymakers, and research institutions, ensuring that supply chains are not only low carbon but also ecologically friendly and economically viable.

5.2 Socio-economic challenges

Challenge 1. Lack of a Common Methodology for Valuing Energy Storage Services: one major obstacle is the absence of a standardized approach to assess the value of energy storage. Without a common methodology, it is difficult to quantify how storage technologies contribute to system operability, frequency containment, flexibility, and grid stability. This hampers market recognition of the full benefits that storage, especially hybrid systems, can provide, making it harder to develop viable business models or attract investment.

Challenge 2. Lack of visibility on future system needs: the lack of long-term visibility regarding system flexibility requirements creates uncertainty for investors and market players. Current system planning largely focuses on renewable energy deployment but lacks clarity on how flexibility services will be provided in the short and long term. Transparent investment signals, access to reliable data, and clearer market frameworks are essential to guide stakeholders and ensure coordinated investment planning. Without this visibility, storage developers struggle to anticipate how their assets will be integrated and valued in the evolving energy system.

Challenge 3. Lack of investments and insufficient revenue streams: The financial viability of energy storage projects remains one of the most pressing challenges hindering large-scale deployment. Currently, the business case for storage, particularly hybrid systems, relies heavily on electricity price arbitrage and the provision of balancing services. However, both revenue streams are subject to significant price volatility and volume risk, making them unstable foundations for long-term investment. Although storage facilities offer considerable added value by supporting renewable generation, stabilizing wholesale markets, and providing green electricity to household, commercial, and industrial consumers, this value is not yet fully monetized.

Financial risk is further compounded by revenue uncertainty across different markets. Typically, the business case of a storage asset depends on revenue from multiple sources: capacity markets, energy price arbitrage, and system services. The proportional contribution of each of these revenue streams can vary considerably over the lifetime of a storage asset. For instance, arbitrage revenues tend to be minimal in the early years but may grow as the share of renewable generation increases. Yet, the exposure of arbitrage to price fluctuations reduces the bankability of storage projects, particularly under current market conditions.

Additionally, short contract lengths, especially in balancing services, exacerbate revenue volatility. In many European markets, system operators increasingly offer contracts on a daily or hourly basis, making it difficult for developers to secure stable long-term income streams. Capacity markets also present challenges, as energy storage assets are often subject to derating based on export capacity and duration. For example, in Ireland, capacity payments for storage are adjusted downward, with the derating factor decreasing by about 3% annually, a trend expected to continue as storage deployment grows.

Moreover, the fragmented procurement of system services further weakens the business case. Services are typically procured in silos, limiting opportunities for revenue stacking. This approach can force developers to deploy separate assets for distinct services rather than leveraging the full potential of hybrid storage systems, thus impairing economic efficiency and project viability.

Without a stable, predictable, and diversified revenue framework, attracting the necessary investments to scale up hybrid energy storage systems will remain a significant challenge.

Challenge 4. Geographical dependency: the profitability and deployment potential of storage systems are heavily influenced by local conditions such as grid infrastructure, renewable resource availability, and market structure. As a result, certain regions may see more favorable conditions for deploying hybrid storage systems, while others may face significant barriers, leading to unequal growth and scalability across Europe.

Challenge 5. Price Disparities for Behind-the-Meter Storage: Behind-the-meter (BTM) storage solutions face structural disadvantages compared to large-scale producers. These systems often receive lower compensation when feeding electricity into the grid, while being subjected to high retail electricity prices when drawing power. This discrepancy weakens the business case for BTM storage participation in grid services, discouraging investment at the household and commercial levels.

Challenge 6. High Costs of Energy Storage Technologies: reducing the costs of energy storage technologies, both capital expenditure and operational expenditure, remains critical. Lowering costs through economies of scale, material innovations, and optimized supply chains is necessary to ensure that hybrid energy storage solutions are competitive and accessible across markets.

Challenge 7. Safety and Risk Management in Hybrid Systems: as hybridization of energy storage technologies becomes more prevalent, safety challenges grow in complexity. Ensuring the early detection of safety risks, predictive diagnostics, and proper aging control is vital to prevent failures and maintain public trust. This includes establishing standardized safety protocols that can be applied across the various technologies integrated within hybrid systems[62].

5.3 Legislative challenges

Challenge 1. Lack of Market Transparency: current electricity market frameworks tend to focus primarily on large-scale energy storage solutions, often neglecting smaller or decentralized systems. As a result, the full contribution of energy storage technologies—particularly small and hybrid systems—is not fully accounted for by network operators. This lack of visibility places smaller storage solutions at a disadvantage compared to

[62] Workshop on energy conversion and storage days, Karlsruhe, 2023. 'Challenges of grid connected stationary storage'. EnBW company.

large-scale assets and limits their participation in flexibility markets.

Challenge 2. Incomplete Implementation of the Clean Energy Package: The EU's Clean Energy Package has been unevenly implemented across Member States. In several cases, a clear legal definition of energy storage is still missing, resulting in fragmented treatment of storage technologies and inconsistent policy application.

Challenge 3. Lack of Definition and Standards for "Hybrid Energy Storage": Despite the growing relevance of hybrid energy storage systems, there is no formal regulatory definition or standardized framework that recognizes their specific operational characteristics. This absence creates legal uncertainty and hinders the deployment and integration of hybrid solutions.

Challenge 4. Complex and Lengthy Licensing Procedures: Energy storage projects, particularly large-scale installations, continue to face burdensome permitting and licensing processes. Streamlining, digitizing, and setting clear, short deadlines for approvals are necessary to accelerate the deployment of storage projects.

Challenge 5. Lack of Market Products for Ancillary Services: Currently, energy storage is not fully remunerated for the range of services it can provide. There is an absence of dedicated market products to support services such as congestion management, curtailment reduction, fast-response balancing, voltage control, and black start capabilities. Without appropriate mechanisms, storage assets cannot capture the full value of their contribution to grid stability.

Challenge 6. Lack of Regulatory Incentives to Reduce Curtailment and Replace Gas Peaking Plants: Transmission System Operators (TSOs) are required to keep renewable curtailment (downward redispatch) below 5% where economically feasible, but this obligation applies only to Member States with less than 50% renewable electricity penetration. As more countries exceed this threshold, no incentives exist to minimize curtailment, potentially limiting storage's role in reducing reliance on fossil fuel backup plants.

Challenge 7. Lack of a Regulatory Definition for 24/7 Renewable Energy: Although Power Purchase Agreements (PPAs) are critical for renewable energy deployment and consumer price protection, the concept of 24/7 renewable energy is not yet codified in EU law. Establishing clear definitions and frameworks for 24/7 renewable sourcing is essential to promote continuous, clean energy supply supported by storage.

Challenge 8. Implementation Gaps in European Electricity Legislation, Especially for Long-Duration Storage: Existing EU electricity legislation lacks explicit provisions to support long-duration storage solutions. As energy systems evolve, dedicated policies recognizing the unique value of long-duration and hybrid storage will be required.

Challenge 9. Lack of Favorable Market Conditions: Non-frequency ancillary services such as voltage control and black start capabilities remain largely undervalued and are often not remunerated. Establishing fair and competitive market conditions for these services is essential to unlock the full potential of hybrid energy storage solutions.

Challenge 10. Insufficient Financial Instruments: While balancing markets may offer liquidity in some cases, many market segments, particularly those suited to hybrid systems, still lack sufficient financial instruments to support competition and investment. This absence exacerbates risks and limits investor confidence.

Challenge 11. Inconsistent Grid Fees Across the EU: Energy storage systems face inconsistent treatment regarding grid fees across Member States. Different technologies, locations (behind-the-meter vs. front-of-the-meter), and ownership models are subject to varying tariff structures, often misaligned with EU-level principles of cost-reflectiveness as outlined in the Electricity Market Regulation. This lack of harmonization creates barriers to efficient deployment.

Challenge 12. Taxation Barriers and Double Taxation Issues: The current European Energy Taxation Directive (Directive 2003/96/EC) often leads to double taxation on stored electricity. Taxes, surcharges, and grid tariffs are typically imposed both when electricity is stored and when it is later fed back into the grid. This penalizes many storage applications, including arbitrage and ancillary services[63]. The ongoing revision of the ETD provides a crucial opportunity to simplify rules and eliminate double taxation[64].

Challenge 13. Safety Challenges Associated with Emerging Technologies: As new storage technologies and hybrid systems are introduced; additional safety measures are necessary to protect both workers and the public. Regulatory frameworks must address these emerging risks and ensure safe operation throughout the life cycle of storage systems.

Challenge 14. Monetization of Services Provided by Storage Systems: There is currently no clear framework for adequately compensating all services provided by storage systems, particularly smaller-scale and seasonal or long-duration storage. Remuneration models often favor large-scale players, overlooking the critical role of smaller contributors and aggregators in maintaining grid stability and reducing curtailment. The lack of consistent, transparent mechanisms for monetizing flexibility and ancillary services adds financial uncertainty and discourages investment.

Challenge 15. Energy Storage Classification under "Generation" or "Consumption": In many national legal systems, energy storage is categorized as either generation or consumption, leading to regulatory ambiguity and additional barriers. A dedicated legal classification for energy storage—as a unique pillar alongside generation, transmission, distribution, and consumption—would help remove unnecessary obstacles and clarify its role in the energy system.

Challenge 16. Need for Competitive Bidding Processes: Attracting investment in new and hybrid storage technologies requires transparent and competitive bidding processes. Well-designed tenders and auctions would provide stable investment signals, reduce financial risk, and promote cost-effective deployment of storage assets.

Challenge 17. Reliable Regulatory Policies for Second-Life Applications: To enable the reuse of storage components, particularly batteries, in second-life applications, a comprehensive legal framework is needed. Clear policies governing safety, performance standards, and environmental compliance will ensure that second-life systems can be deployed effectively.

Challenge 18. Development of Transport Regulations for Energy Storage Systems: Currently, there is no standardized legal framework regulating the transport of energy storage systems across Europe, particularly regarding health and safety measures tailored to the specific risks associated with different technologies (e.g., lithium-ion, flow batteries). Establishing clear, harmonized rules for the transport and handling of energy storage systems is essential.

[63] Study on energy storage. Entec. Energy transition expertise centre. 2023

[64] Directive 2003/96 – ETD. European Commission

6. Benchmarking and KPIs

Complexity of KPI Evaluation in Hybrid Energy Storage Systems. As Hybrid Energy Storage Systems (HESS) are increasingly being recognized as a versatile solution to the limitations inherent in single-type energy storage technologies, benchmarking and evaluating the Key Performance Indicators has an increased degree of complexity introduced by the combination of different storage technologies (EES, CES, TES, MES, SMES).

HESS can offer enhanced performance characteristics, such as improved energy and power density, better cycle life, and optimized cost efficiency. However, unlike single storage technologies, where key performance indicators (KPIs) are relatively straightforward to define and measure, hybrid systems require a more refined approach. The challenge lies in the interaction between different storage components, each with distinct performance characteristics, efficiencies, and limitations. Therefore, developing a comprehensive set of KPIs for HESS necessitates categorizing them based on how they are estimated or influenced by the hybrid nature of the system.

To address these complexities, KPIs can be categorized based on:

1. **Method of Aggregation:**
    - Weighted Average KPIs: Derived from the proportional contributions of each storage component.
    - Cumulative KPIs: Reflect the total contributions of all components.
    - Dominant- or Limiting-Technology KPIs: Determined by the best or weakest-performing technology in the system.
2. **Dependency on Operational Profile:**
    - Dynamic KPIs: Require real-time modeling or simulation due to dependency on varying conditions.
    - Static KPIs: Based on the intrinsic features of system components.

These categories will help clarify the complexities associated with benchmarking hybrid systems and provide a structured approach to their evaluation.

Weighted average KPIs in hybrid systems represent metrics where the performance of the overall system is a function of the proportional contributions from each storage component. KPIs in this group are essential for understanding how different technologies synergize to offer improved or optimized performance.

Cumulative KPIs are those that reflect the total contribution of each component in the system, resulting in a system-wide metric. These KPIs are crucial for understanding the overall capacity, cost, and environmental impact of the hybrid system, making them pivotal in large-scale applications like grid storage or industrial energy management. Dominant- or Limiting- Technology Influenced KPIs are determined by the performance of the best or weakest component within the hybrid system. The strongest technology sets the upper limit for certain KPIs, while the weakest technology might limit overall system performance. KPIs in this group are critical to balance strengths and mitigate weaknesses in hybrid system configurations.

Dynamic KPIs require real-time simulation or extensive modeling to accurately capture system performance under varying conditions. These KPIs are particularly important for applications where the system operates in highly variable environments, such as grid balancing or renewable integration. Finally, Static KPIs are less about system performance in operation and more about the intrinsic properties of the system that affect its deployment and long-term viability.

Historically, benchmarking and quantifying KPIs have been relatively straightforward at the single technology level, where specific metrics such as energy density, efficiency, and cycle life were directly attributed to a particular storage technology. However, with hybrid energy storage systems, we must move beyond technology-specific metrics to define **technology-neutral KPIs** that can effectively assess storage performance at hybrid storage **system** and the **application level**.

This transition is necessary to enable meaningful comparisons between different HESS configurations for diverse energy storage applications.

The next section introduces a glossary table of all KPIs, categorized by whether they are system- or application-level.

The table categorizes **KPIs** for HESS into **technical, economic, and environmental** metrics, providing a structured approach to evaluating storage solutions. A key distinction is made between **system-level** and **application-level KPIs**.

System-level KPIs assess the performance of a specific hybrid or single energy storage technology (e.g., cycle lifetime, round trip efficiency, volumetric energy density) and are interpretable independent of the operational context. In contrast, **application-level KPIs** evaluate storage performance at the energy system application (e.g., grid services, cost-of-energy, emission reductions), which requires a holistic assessment of storage co-operating with generation and load in a realistic application setting. The **aggregation method** further defines how these KPIs are measured for combinations of storage systems—whether as *cumulative* (summing contributions of all components), *weighted average* (proportional contributions from each storage unit), or *limiting technology*-based (determined by the weakest-performing component). This classification ensures that KPIs are aligned with their intended scope, facilitating fair benchmarking and decision-making across different storage applications.

Section 6.2 introduces a list of both required **system-level** and **application-level KPIs** tailored for the following applications:

1. **Industry** – power-intensive processes, high-temperature storage, and industrial decarbonization.
2. **Grid** – frequency regulation, power smoothing, and fossil fuel plant repurposing.
3. **Off-Grid** – cold climates, hot climates, and energy community storage.
4. **Transport** – charging stations, heavy-duty transport energy regeneration and peak demand of power, rail, waterborne, and airborne applications.
5. **Buildings** – behind-the-meter storage for residential and commercial energy management.

Each section includes a comprehensive breakdown of **technical, economic, and environmental KPIs**, along with current benchmarks, **2030 targets** and, where feasible or predictable, **2040 targets** to provide a structured evaluation framework for hybrid energy storage solutions.

6.1 Key Performance Indicators Glossary

KPI Glossary for Hybrid Energy Storage Systems						
KPI	Abbrev.	Unit	Description	Type	Level	Aggreg. Meth.
Ramp-up Time / Response Time	-	ms, s, min	Power-related storage/retrieval speed (charge/discharge speed).	TECH	APP	DLT
Frequency Regulation Capability	-	% deviation	Effectiveness of an integrated energy storage system in maintaining grid frequency stability by responding to power imbalances at the system level.	TECH	APP	WA
Loss of Power Supply Probability	LPSP	%	Probability of failing to meet electrical demand annually.	TECH	APP	WA
Loss of Heat Supply Probability	LHSP	%	Probability of failing to meet heating demand annually.	TECH	APP	WA
Range	-	Km, miles	Maximum distance a vehicle can travel on a single full charge or refueling cycle, critical for evaluating energy storage performance in transport applications.	TECH	APP	-
Charging time (AC or DC)	-	h	Time required to fully recharge the energy storage system, depending on the charging method (AC or DC). Most relevant for transport applications.	TECH	APP	-
Discharge duration	-	h, days	Time the system can sustain rated power delivery without recharging.	TECH	SYS	-
Round Trip Efficiency	RTE	%	Percentage of electricity put into storage that is later retrieved.	TECH	SYS	WA
Self-Discharge	-	% / time	Proportion of stored energy lost over time due to self-discharge.	TECH	SYS	WA
Depth of Discharge	DoD	% of capacity	Percentage of total capacity discharged before recharging is needed.	TECH	SYS	DLT
Cycle Lifetime / Durability	-	Cycles	No. of equivalent full cycles a system can operate before reaching a certain state of health (e.g., 80% for Lithium-Ion batteries).	TECH	SYS	WA
Calendar Lifetime	-	years	System degradation over time due to temperature, state of charge, and other factors.	TECH	SYS	WA
Volumetric Energy or Power Density	-	kWh/m^3, kW/m^3	Usable energy or power per unit volume.	TECH	SYS	WA
Gravimetric Energy or Power Density	-	kWh/kg, kW/kg	Usable energy or power per unit mass.	TECH	SYS	WA
Weight	-	kg	Total weight of the energy storage system. Most relevant for transport applications.	TECH	SYS	C
Storage Capacity	-	kWh, MWh, Ah	Quantity of stored energy in the system or available after full charge.	TECH	SYS	C
Continuous Power	-	kW	Maximum charging and discharging power sustained over a minimum period.	TECH	SYS	C
Recharging Energy	-	kWh, MWh	Amount of energy required to fully charge the storage system.	TECH	SYS	C
Material Use (Criticality, Toxicity, etc.)	-	kg, toxicity, criticality	Type and amount of materials needed for energy storage.	TECH	SYS	C

Complexity	-	Complexity index	The level of complexity involved in integrating and managing the different components.	TECH	SYS	-
Dynamic Load Response	-	Performance index	The ability of the system to respond to changes in load demand over time.	TECH	SYS	-
Capital Expenditure	CAPEX	€/kWh, €/kW	Upfront investment cost for energy storage assets.	ECO	APP	C
Operational Expenditure	OPEX	€/kWh	Recurring operational costs, including maintenance, personnel, and energy costs.	ECO	APP	C
Total Expenditures	TOTEX	€/kWh	Sum of CAPEX and OPEX.	ECO	APP	C
End of Life Expenditure	EOLEX	€/kWh	Costs related to decommissioning, recycling, or disposal of storage components.	ECO	APP	C
Levelized Cost of Electricity	LCOE	€/kWh, €/kW	Cost of generating electricity per kWh over the system's lifetime, including capital, maintenance, and operational costs.	ECO	APP	WA
Levelized Cost of Heat	LCOH	€/kWh, €/kW	Cost of generating heat per unit over the system's lifetime.	ECO	APP	WA
Levelized Cost of Storage	LCOS	€/kWh/yr	Cost of storing and delivering energy per kWh over the system's lifetime, accounting for capital, maintenance, operational costs, efficiency losses, and degradation.	ECO	APP	WA
Life Cycle Cost	LCC	€/energy or power unit	Total cost of ownership over the full life cycle, including CAPEX, OPEX, and EOLEX.	ECO	APP	C
Return on Investment	ROI	years	Time required to recoup the initial investment.	ECO	APP	WA
Technological Readiness Level	TRL	Rank	Maturity assessment of a storage technology.	ECO	SYS	DLT
System Readiness Level	SRL	Rank	Readiness level of an entire storage system.	ECO	SYS	DLT
Manufacturing Readiness Level	MRL	Rank	Maturity of manufacturing processes for storage technologies.	ECO	SYS	DLT
Carbon Footprint	-	$kgCO_2eq$	The total greenhouse gas emissions associated with the system.	ENV	APP	C
Carbon Footprint/ Specific GHG Emissions	GHG	kg CO_2-eq/MWh	Greenhouse gas emissions over the system's life cycle	ENV	APP	C
Global Warming Potential	GWP	kg CO_2-eq	Evaluates radiative forcing due to the emission of 1 kg substance relative to the equal amount of CO_2 over different time horizons.	ENV	APP	C
Cumulative Energy Demand	CED	MJ-eq.	Total energy consumption (fossil, nuclear, renewable) over the life cycle.	ENV	APP	C
Resource Use - Energy Carriers	ADP-fossil	MJ	Biotic resource depletion, including fossil fuel reserves.	ENV	APP	C
Resource Use - Minerals & Metals	ADP	kg Sb-eq	Abiotic depletion of fossil and metal resources.	ENV	APP	C
Particulate Matter / Respiratory Impact	-	Disease incidence	Health impact from fine particulate emissions.	ENV	APP	C
Toxicity (Human & Ecological)	-	Qualitative	Impact of storage technology on human health	ENV	APP	WA
Ozone depletion potential	ODP	kg CFC-11eq	ODP is the ratio between the amount of ozone destroyed by a unit of a substance "x" and a reference substance, normally taken as CFC-11.	ENV	APP	C

Photochemical ozone formation potential	POCP	kg C_2H_4eq	This indicator quantifies the relative abilities of volatile organic compounds to produce ground level ozone.	ENV	APP	C
Acidification potential	AP	kg SO_2eq	It is connected to acid deposition of acidifying contaminants on soil, groundwater, surface waters, biological organisms, ecosystems, and substances.	ENV	APP	C
Eutrophication potential	EP	kg PO_4^{3-}eq	Eutrophication includes all impacts due to excessive levels of macro-nutrients in the environment caused by emissions of nutrients to air, water and soil. Eutrophication potential is based on the stoichiometric procedure of Heijungs (1992) and expressed as kg PO_4 equivalents per kg emission.	ENV	APP	C
Land Use	Lu	Kg C deficit	Measure of the changes in soil quality (Biotic production, Erosion resistance, Mechanical filtration).	ENV	APP	C
Land Footprint	-	m^2/kWh	Surface area required per unit of stored energy	ENV	APP	WA
Ionising radiation - human health	IR	kg U235 eq	Damage to human health and ecosystems linked to the emissions of radionuclides.	ENV	APP	C
Energy Access Improvement	-	% of population served	Measures how storage contributes to providing reliable electricity in underserved regions	SOC	APP	-
Community Acceptance	-	%	Public perception & adoption of energy storage solutions.	SOC	APP	-

6.2 List of KPIs for hybrid applications

Key Performance Indicators for Industry applications				
KPI	Unit	Current Benchmark	2030 Target	2040 Target
Cycle Lifetime	cycles	10,000+ (70% DoD, 2h disch.) [65,66] (Li-ESS)	15,000	20,000
Lifespan	years	15	20	> 25
Round Trip Efficiency	%	≥95[67] (Li-ESS)	> 97 (Li-ESS)	> 98 (Li-ESS)
Response Time	ms	100-15,000	100-1,000	<100
Availability*	%	97-98	99	> 99
Self-Discharge	% / month	2-5 (EES) 10-20 (Sensible TES) 5 (Thermochemical)**	1-3 (EES) 5-10 (Sensible TES) 3 (Thermochemical)**	1 (EES) 5 (Sensible TES) 1 (Thermochemical)**
Initial Capital Cost (CAPEX)***	€/kWh	200-300 (Li-ESS) 500-1,500 (hybrid EES-CES)[68] 0.1-25 (TES for T≤160ºC)[69] 25-120 (TES for T≥160)[70]	<200 (Li-ESS) 300 (hybrid EES-CES) 60-95 (TES for T≥160)[69]	<150 (Li-ESS) 200 (hybrid EES-CES) < 90 (TES for T≥160)
Operational Expenditure (OPEX)	€/kWh/year	20	10	5
End of Life Expenditure (EOLEX)	€/kWh	50	25	10
Levelized Cost of Electricity (LCOE)	€/kWh	0.15-0.40	0.10	0.05
Levelized Cost of Storage (LCOS)	€/kWh	0.15-0.25	0.05	0.02
Lifecycle GHG Emissions	gCO_2eq/kWh	90-250	< 50	< 20

*Relevant for industries with standalone power systems (e.g., remote manufacturing sites, data centers with independent energy supply). For industries connected to the grid, availability may be less critical, as grid redundancy can compensate for storage failures.
** Thermochemical TES shows promising low-self discharge and long-duration capabilities, but current TRL is low (4-6)
*** Temperature range according to authors' estimation

65 https://www.morlus.com/en/
66 https://pknergypower.com/liquid-cooling-battery-energy-storage-series/
67 https://cdn.enfsolar.com/z/pp/lgs60d5dcbfd3689/2.-BYD-BATTERY-BOX-PREMIUM-HVM.pdf
68 https://docs.nrel.gov/docs/fy23osti/85332.pdf
69 Geyer, M., Trieb, F. and Giuliano, S. (2020) Repurposing of existing coal-fired power plants into Thermal Storage Plants for renewable power in Chile. Bonn, Germany.
70 IRENA (2020), Innovation Outlook: Thermal Energy Storage, International Renewable Energy Agency, Abu Dhabi.

Key Performance Indicators for Grid applications				
KPI	Unit	Current Benchmark	2030 Target	2040 Target
Cycle Lifetime	cycles	10,000+ (70% DoD, 2h disch.) (Li-ESS) > 1,000,000 (SC) 200,000-1,000,000 (FW)	15,000 (Li-ESS) > 1,500,000 (SC) > 1,000,000 (FW)	20,000 (Li-ESS)
Lifespan	years	15 (Li-ESS) > 20 (FW) > 15 (SC)	20 (Li-ESS)	> 25 (Li-ESS)
Round Trip Efficiency	%	≥96 [71],(Li-ESS) 35 (TES) 92 (SC) 80-90 (FW)	>97(Li-ESS) 40 (TES) 95 (SC) > 90 (FW)	>98(Li-ESS) >40 (TES) > 95 (SC)
Response Time	ms	100-15,000 * $60\cdot10^3$-$216\cdot10^6$ (TES)** 5-10 (SC, FW)	100-1,000 <$180\cdot10^6$ (TES) < 5 (SC, FW)	<100 <$150\cdot10^6$ (TES)
Frequency Regulation Capability	% deviation	± 0.1		
Energy Density	kWh/m^3	26-80 (TES) 200-500 (Li-ion)	> 500 (Li-ion)	> 700 (Li-ion)
Initial Capital Cost (CAPEX)	€/kWh	<282[§](Li-ESS)[72] 20-55 (TES) 20,000-60,000 (SC)*** 12,000-50,000 (FW)	<150(Li-ESS) 15-30 (TES) < 60,000 (SC) 10,000-20,000 (FW)	<100(Li-ESS) < 20 (TES) < 40,000 (SC) < 20,000 (FW)
Levelized Cost of Storage (LCOS)	€/kWh	0.15-0.25 0.08-0.10 (TES) 0.443 (SC)	0.05-0.10 <0.09 (TES) < 0.4 (SC)	< 0.05 <0.085(TES)
Manufacturing Readiness Level (MRL)	-	8-9 (Li-ion systems) 8-9 (sensible TES) 8-9 (FW) 9 (SC) 6-7 (flow batteries) 4-6 (H_2) 4-5 (latent TES and thermochemical)	**4-6 (HESS)** 8-9 (flow batteries) 7-8 (H_2) 6 (latent TES) 5 (thermochemical)	**7-8 (HESS)** 7 (latent TES) 6 (thermochemical)
Lifecycle GHG emissions	gCO_2eq/kWh	80-200	< 40	< 20

[§] BNEF's Long-Duration Energy Storage Cost Survey 2023, 4hr BESS, costs expected to be halved in 2025 given that the cost of Turnkey systems (including all project equipment (DC Block+PCS+EMS) excluding EPC and grid connection), is 153€ according to BloombergNEF, industry experts[73], and low sub-100$ USD for Power Chinas 16GWh BESS Tender[74]

* The wide range of response times reflects the variety of technologies used (e.g., batteries, pumped hydro, gravitational storage). In HESS, integrating multiple technologies allows maximizing their strengths. Since response time is limited by the slowest component, control strategies should prioritize faster technologies for immediate response. A target of 100-1000ms by 2030 is recommended.

**The TES response time is given by the thermal power cycle response time

*** Supercapacitor (SC) values are included for comparison, but SCs are typically not used for bulk energy storage due to their low energy density and high cost per kWh.

[71] https://www.altenergymag.com/article/2023/11/increasing-life-and-cylce-life-of-energy-storage-systems/40558 CATL EnerOne BESS

[72] https://renewablesnow.com/news/ldes-competing-better-with-lithium-ion-batteries-bnef-study-859422/

[73] https://www.linkedin.com/feed/update/urn:li:activity:7282327168028704768/?updateEntityUrn=urn%3Ali%3Afs_feedUpdate%3A%28V2%2Curn%3Ali%3Aactivity%3A7282327168028704768%29

[74] https://www.energy-storage.news/mind-blowing-bids-power-chinas-16gwh-bess-tender-state-owned-firms-market-share/

Key Performance Indicators for Off-grid applications				
KPI	Unit	Current Benchmark	2030 Target	2040 Target
Cycle Lifetime	cycles	5,000	10,000	15,000
Round Trip Efficiency	%	≥95[75](Li-ESS) 30-35 (TES)	>97(Li-ESS) >35 (TES)	>98(Li-ESS) >40 (TES)
Response Time	ms	100-15,000* $60 \cdot 10^3$-$100 \cdot 10^6$ (TES)	100-1,000 $<90 \cdot 10^6$ (TES)	<100 $<80 \cdot 10^6$ (TES)
Loss of Power Supply Probability (LPSP)	%	< 1		
Loss of Heat Supply Probability (LHSP)	%	< 1		
Self-Discharge	% / month	2-5 (EES) 10-20 (latent heat TES)**	1-3 (EES) 5-10 (latent heat TES)	1 (EES) <5 (latent heat TES)
Initial Capital Cost (CAPEX)	€/kWh	200-300[76](Li-ESS) 1,500-2,000 [77] (hybrid EES-CES) 40-100 (TES)	<250 (Li-ESS)[77] 800 (hybrid EES-CES) <90 (TES)	<175 (Li-ESS) < 500 (hybrid EES-CES) <80 (TES)
Levelized Cost of Electricity (LCOE)	€/kWh	0.15-0.40 [78]	0.10-0.25 [78]	0.05-0.15 [78]
Levelized Cost of Storage (LCOS)	€/kWh	0.25-0.50 [79]	< 0.20	< 0.10
Lifecycle GHG Emissions	gCO_2eq/kWh	100-250 [80]	< 50 [80]	< 20
Diesel Generator Usage Reduction	% reduction	50-80	> 90	100
Flexibility Factor***	-	5 (EES) 2-3 (CES) 1-3 (TES)	5 (EES) 3-4 (CES) 2-3 (TES)	5 (EES) 4-5 (CES) 3-4 (TES)

* The wide range of response times reflects the variety of technologies used (e.g., batteries, pumped hydro, gravitational storage). In HESS, integrating multiple technologies allows maximizing their strengths. Since response time is limited by the slowest component, control strategies should prioritize faster technologies for immediate response. A target of 100-1000ms by 2030 is recommended.

** Value assumes moderate- to well-insulated off-grid PCM systems.

*** Qualitative indicator (scale 1-5) representing the system's ability ro respond to varying loads, sourcesm and response needs in off-grid systems.

[75] https://cdn.enfsolar.com/z/pp/lgs60d5dcbfd3689/2.-BYD-BATTERY-BOX-PREMIUM-HVM.pdf

[76] https://bts.net.ua/eng/alternative-energy-sources-and-generators/energy-storage/un-versalne-skhovishche-elektroenerg-ess-eco-e233ls-lifepo4-z-r-dinnim-okholodzhennyam/

[77] https://atb.nrel.gov/electricity/2024/utility-scale_pv-plus-battery

[78] C. Kost, "Study: Levelized Cost of Electricity- Renewable Energy Technologies," 2024. [Online]. Available: www.ise.fraunhofer.de

[79] https://www.pnnl.gov/projects/esgc-cost-performance/lcos-estimates

[80] Life Cycle Greenhouse Gas Emissions from Solar Photovoltaics," *NREL*

Key Performance Indicators for Transport applications				
KPI	Unit	Current Benchmark	2030 Target	2040 Target
Road Transport (Heavy duty)				
Lifetime	km	>1,200,000	1,400,000	1,500,000
Continuous Power	kW	200-600 [81,82]	300-600 [81,82]	
Charging time (AC)	h	11 (43kW charger) [83]	-	-
Charging time (DC)	h	0.75-1.5 (375kW charger) [84]	0.65-1.1 (750kW Charger) [$]	≤0.5 (≥1000kW Charger) [$]
VED (pack)	kWh/l	256	275	300
GED	kW/kg	285	300	>300
[Controlled]/Operating Temperature	°C	[20 to 35] / -30 to +55		
Weight (ES system)	kg	3000	2800	<2800
Lifespan	years	10	15	20
Range	km	~500 [85]	800	1000
Lifecycle GHG Emissions	gCO_2eq/km	540 [86]	450	400
Waterborne Transport [†]				
Operating lifespan	hours	40,000 [87, 88]	80,000 [87,88]	< Ship/vessel lifetime [87]
Cycle Lifetime	cycles	50,000 (25% DoD, 4C) [87]	>80,000 (25% DoD, 4C) [87]	
GED (cell level)	kWh/kg	250 [87]	350	600-700
VED (cell level)	kWh/l	600-700 [87]	800-1,000	1500-1800
CAPEX	€/kWh	700-1,400 [87, 88]	300-1,000 [87, 88]	250-600
Cell/ESU[††] weight ratio	%	60 [87]	70	
Cell/ESU[††] volume ratio	%	30-40 [87]	60	
Hazard level [¥]	-	3-4 [87]	≤ 2	≤ 1
Type approvals [¥¥]	No. of approvals	3 (Hybrid systems), 3 (Battery systems), 4 + 4 Approvals in Principle (Fuel cells, Ammonia systems)	20	50
Airborne Transport				
Technology Readiness Level (TRL)	-	TRL 9 (light aircraft) *	-	-
		TRL 4-5 (Commuter, 19 pax, and regional flights, 30-70 pax)	TRL 7 (flight testing)	TRL 9 (first commercial entry-into-service for hybrid electric regional flights by 2035)
		n.a. (short-medium, 120-250 pax, and long-range flights, 300+ pax)	TRL 5-6 (more electric aircraft)	TRL 9 (entry-into-service for the "more electric" long range aircraft by 2040) **
Cycle Lifetime	cycles	1000-2000 (70% DoD) [87]	2000+	
GED	kWh/kg	230-260 (Cell) [87]	400 [89]	700 [89]
		170-250 (Module/Pack) [87]	350 [89]	500-600 [89]
Discharge rate	-	1-3 C (charge) [89]	3-5 C (charge)	
		2-5 C (discharge) [89]	5-10 C (discharge)	
GHG emissions reduction	% of CO_2 emissions	-	-	40% reduction in hybrid electric configuration (Commuter, regional flights).

[81] https://www.volvotrucks.com/en-en/trucks/electric/volvo-fl-electric.html
[82] https://www.batterydesign.net/2022-volvo-truck-battery/
[83] https://stpi.it.volvo.com/STPIFiles/Volvo/FactSheet/ESS180K,ESS270K,ESS360K,ESS450K,ESS540K_Eng_08_337548981.pdf
[84] https://www.man.eu/ntg_media/media/en/content_medien/doc/bw_master/truck_2/man-etruck-brochure.pdf
[85] https://www.man.eu/global/en/truck/all-models/the-man-tgx/the-man-etgx/overview.html
[86] https://www.scania.com/content/dam/group/press-and-media/press-releases/documents/Scania-Life-cycle-assessment-of-distribution-vehicles.pdf
[87] Batteries Europe "Research and Innovation Roadmap" 2023
[88] Clean Hydrogen Partnership "Strategic Research and Innovation Agenda" 2021 – 2027
[89] Helmut Kühnelt *et al* 2023 *J. Phys.: Conf. Ser.* 2526 012026

				2-4 % reduction in “more electric” configuration (medium- and long-range)
Rail Transport				
Operating lifespan (hybrid)	hours	20,000	30,000	> 40,000
GED (battery cell level)	kWh/m³	250	350	600-700
VED (battery cell level)	kW/m³	600-700	800-1,000	1500-1800
Range	km	50-200 (Battery trains) 600-1000 (hydrogen powered trains)	1000-1500 (hybrid trains)	> 2000 (hybrid trains)
Power consumption	kWh/km	10-15 (Battery trains) 3-5 (hydrogen powered trains)	< 5 (hybrid electric-fuel trains)	
TRL (charging infrastructure)	-	TRL 8-9 (electric stations) TRL 6-7 (hydrogen refuel) TRL 5-6 (hybrid: emerging, combined systems still in testing)	TRL 7 (hybrid: pilot projects, initial commercial deployment)	TRL 8-9
Hazard level	-	3-4	≤ 2	≤ 1

† Most KPIs listed are relevant to both electrical storage (e.g. batteries) and fuel storage (e.g. hydrogen-systems). Current benchmarks reflect typical ranges observed in individual technologies, while future targets are defined as being applicable for integrated HESS.

†† **ESU:** Energy Storage Unit (including rack, gas exhaust system, battery management system)

¥ **Hazard level:** according to the **EU Council for Automotive R&D (EUCAR) Hazard Level**. Ranking: Level 0 (no Hazard) to Level 7 (explosion)

¥¥ **Type approval:** certification process in the maritime industry that verifies a product's compliance with specific technical standards and regulations. As of March 2025, DNV-GL, ABS, Lloyd’s Register, and Bureau Veritas released type approval for a number of hybrid systems (Transfluid, Kawasaki, and Volvo Penta), battery systems (Corvus Energy Dolphin ESS, EST-Floattech's Octopus®, and PowerTech Systems' PowerRack®), and fuel cells (Ballard Power Systems' FCwave™, Corvus Energy's Pelican FC, EODev's REXH2® Hydrogen FC, Freudenberg's Methanol-Powered FC).

* The only electric aircraft technology that has reached full maturity (**TRL 9**) is the **CS-23 light aircraft**[90]. However, this segment has a minimal impact on commercial air travel and its influence on global aviation markets is negligible.

** “**Hybrid electric**” aircrafts combine conventional fuel-powered engines with electric propulsion systems. “**More electric**” aircrafts focus on the electrification of non-propulsive systems while still relying on conventional jet engine technology for propulsion.

$ Charging time is a function of battery chemistry/cell design/pack design and charging infrastructure. 375kW class chargers, for transport applications, seem common enough to be set as the current benchmark.750kW class chargers are currently available from MAN/ABB and are expected to have wider adoption by 2030 as the charging time would match the regulated 45-minute break for truck drivers in Europe. Megawatt (≥1000kWh) class charges are already entering demonstration phase (MAN[91],Tesla[92],BYD[93])[94]

[90] https://elixir-aircraft.com/the-company/elixir-aircraft/

[91] https://press.mantruckandbus.com/corporate/download/22af6bf8-ae4d-4d33-88b1-343acbce8e87/240321-mtb-pi-abb-man-megawatt-charging-premiere-en.pdf

[92] https://topelectricsuv.com/news/tesla/tesla-semi-all-we-know-feb-2022/

[93] https://www.byd.com/mea/news-list/byd-unveils-super-e-platform-with-megawatt-flash-charging

[94] https://statzon.com/insights/a-megawatt-future-for-hdv-charging-networks

Key Performance Indicators for Buildings applications

KPI	Unit	Current Benchmark	2030 Target	2040 Target
Cycle Lifetime	cycles	5,000	10,000	20,000
Lifespan	years	15-30	20	> 25
Round Trip Efficiency	%	>90[95]	>95	
Energy Density	kWh/m^3	26-80 (TES) 200-500 (Li-ion)	> 500 (Li-ion)	> 700 (Li-ion)
Initial Capital Cost (CAPEX)	€/kWh	600[96] (Li-ESS)[α] 800 (EES) [97] 0.1-35 (TES using sensible heat)[52] 60-230 (TES using latent heat)[52] 15-150 (TES using thermochemical)[52]	<450 (Li-ESS) 400 (EES) <25 (TES using sensible heat)[52] 60-180 (TES using latent heat)[52] 12-80 (TES using thermochemical)[52]	<300(Li-ESS) < 300 (EES) <20 (TES using sensible heat) 50-150 (TES using latent heat) 10-70 (TES using thermochemical)
Levelized Cost of Storage (LCOS)	€/kWh	0.15-0.25 (EES)	0.05 (EES)	0.02 (EES)[98]
Lifecycle GHG Emissions	gCO_2eq/kWh	80-200	< 40	< 20
Energy Access Improvement [β]	% population	Varies by region	+10 %	+ 20 %
Community Acceptance [β β]	%	70%	85 %	95 %

[β] 2030 and 2040 target values may be particularly relevant for regions with limited grid connectivity or unreliable energy access.

[β β] Community acceptance is particularly relevant for EES (especially Li-ion batteries), which often face lower public support due to concerns about safety and environmental impact.

[α]Costs vary dramatically on whether permitting is necessary or not and on if state approved installers are used rather than certified electricians. Configuring on sunwatts.com, a **roof mounted solar + bess + installation** (SKU:CS450-15kW-SolarEdge +20kWh SolarEdge battery & amp) **results in costs of $21700 + $18000 + $19000 respectively +$1000 in shipping costs.** A 12kWh BYD Battery Box premium HVL costs $7600 and a compatible converter (SKU: SBSE7.7-US-50, 7.7kW) costs $ 3550

[95] https://sunwatts.com/16-kwh-lg-chem-lithium-ion-home-battery-resu16h-prime/

[96] https://sunwatts.com/16-kwh-lg-chem-lithium-ion-home-battery-resu16h-prime/ Cost 9000$ installation assumed at 1000$ USD, rounded up.

[97] https://www.sciencedirect.com/science/article/pii/S0360319923032615

[98] HYBRIS project - Deliverable No.1.6 - Levelized Cost of Storage (LCOS) analysis - https://hybris-project.eu/download/d1-6-levelized-cost-of-storage-lcos-analysis-2/

7. Conclusions

The transition to a low-carbon and resilient energy system requires innovative, flexible, and efficient energy storage solutions that can accommodate the variability of renewable energy sources. HESSs represent a key technological response to this challenge, offering the potential to optimize performance, improve system reliability, and support the large-scale integration of renewables such as wind, photovoltaic, and concentrated solar thermal power.

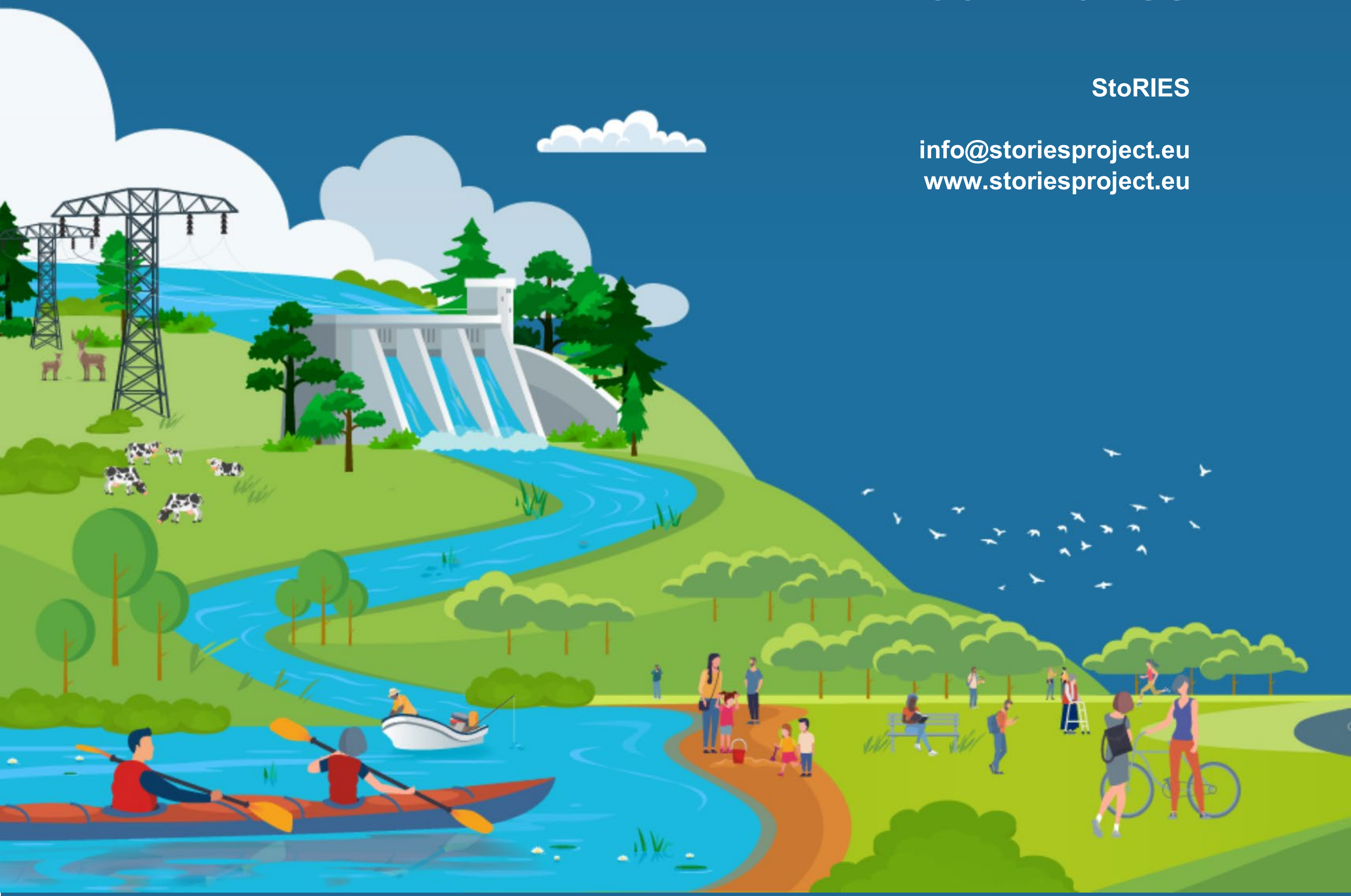
This roadmap has highlighted the strategic importance of HESSs within the broader context of European energy policy and sustainability objectives. By identifying current technology benchmarks, performance targets, and the main technical, socio-economic, and regulatory barriers, it provides a structured foundation for shaping future research and innovation directions. While it does not prescribe detailed development pathways, the roadmap presents a forward-looking perspective on technological evolution and supports the identification of priority areas for action.

These insights are intended to feed directly into the Strategic Research and Innovation Agenda, helping to define the key areas where targeted research, coordinated investments, and supportive policy frameworks will be essential. The successful development and deployment of HESS technologies will not only enhance energy system resilience and efficiency but also accelerate Europe's progress toward a sustainable and decarbonized future.

CONTACT US

StoRIES

info@storiesproject.eu
www.storiesproject.eu



The StoRIES project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No 101036910