European Commission

Energy Storage Systems

KPI Assessment and Prioritisation of R&I Targets

ETIP SNET

European Technology and Innovation Platform
Smart Networks for Energy Transition

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EXECUTIVE SUMMARY

This Position Paper 'KPIs for Energy Storage Systems and prioritisation of R&I targets' is an initiative of the ETIP SNET WG2 (Storage technologies and system flexibilities) with the objective of defining a vision for R&D&I of storage technologies and involving stakeholders in this vision. It analyses different energy storage and conversion technologies, focusing on the specific challenges they face and trying to prioritise and suggest R&I actions to overcome them. Performance Goals are introduced and defined to support the analysis and identify the main challenges. A mapping exercise is performed to define priorities and optimise the R&I strategy to overcome them, as well as a set of KPIs to set targets for the years 2025 and 2031. The paper does not consider battery technology, given the comprehensive list of actions already taken at European level to stimulate the European battery industry and to boost the necessary R&I ecosystem.
Energy storage and conversion technologies can provide the necessary flexibility to the energy system across different timescales. Several technologies are available, and their state of the art showed different level of development and maturity. Some of these are established technologies, while others have yet to demonstrate their potential at scale.
The outcome of this Position Paper is summarised in a set of targets for each of the analysed energy storage technologies. The mapping exercise allowed the authors to prioritise KPIs to focus on in order to measure the effectiveness of R&I efforts to challenge specific Performance Goals and make the respective technology a suitable solution for the decarbonisation path of the European energy system.

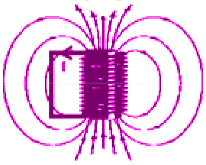
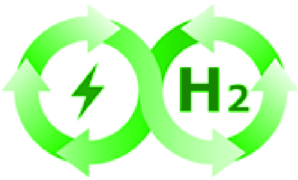
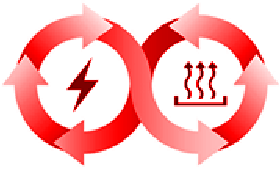
Symbol	Type of technology	Type of storage
	Pumped storage hydropower (PSH)	Mechanical
	Compressed air (CAES)	Mechanical
	Flywheels	Mechanical
	Supercapacitor	Electrical
	Superconducting magnetic ES (SMES)	Electromagnetical
	P2-Gas-2P; P2-Liquids-2P P2-Gas-2Industry (as gas, to heat) P2-Liquid-2Industry (as liquid, to heat) P2-Gas-2Mobility; P2-Liquid-2Mobility	Chemical
	P2-Heat-2P P2-Heat (e.g. heat pump) CSP (Concentrated Solar Power)	Thermal

Figure 1: Legend to the Graphical Summary of the Prioritisation exercise

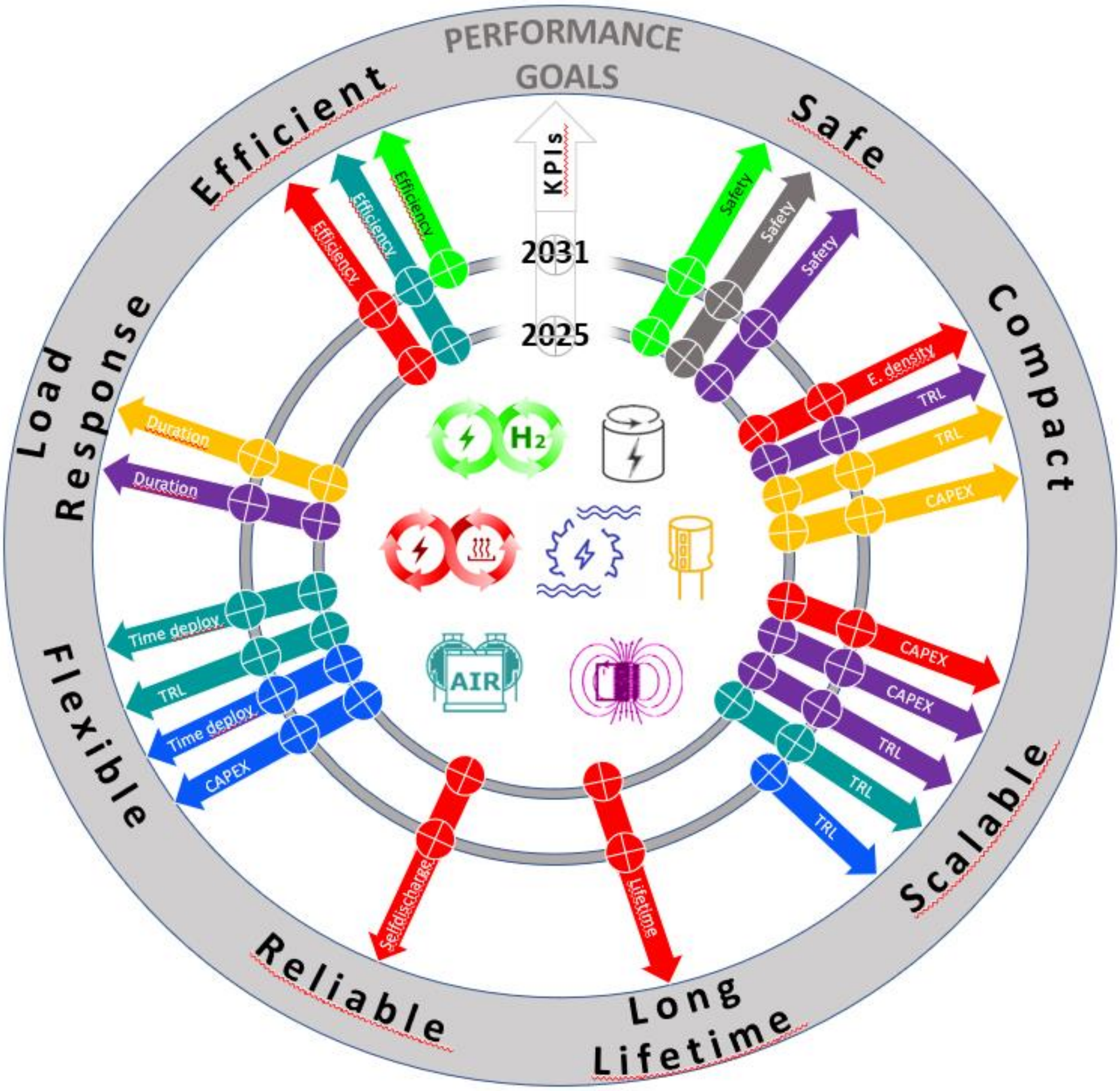


Figure 2: Graphical Summary of the Prioritisation exercise

1. INTRODUCTION

1.1 Today's situation in Europe and requirements for a decarbonised, reliable, adaptable resilient, sustainable, and integrated energy system

Climate change and environmental degradation are an existential threat to Europe and the world. The fossil fuel economy paradigm and supply dependencies are also showing the limits of the EU's role on the world stage and the sooner the EU becomes truly independent and masters its energy system, the better.
REPowerEU[1], the recent Joint European Action for more affordable, secure and sustainable energy, push for a big boost of renewable generation and recognises the role of energy storage especially focusing on hydrogen and industry decarbonisation.
Energy storage has a key role to play in the transition towards a carbon-neutral economy, addressing several of the central principles set in the Clean Energy for all Europeans package.[2] Development and deployment of energy storage technologies is also a central element of the European Green Deal[3] plan that aims to transform the EU into a modern, resource-efficient and competitive economy in line with the Paris Agreement.[4]
It is widely understood that the road that will lead to a carbon-neutral energy system need to rely on an extensive electrification in all sectors of the energy system, combined with massive penetration of renewables, Smart Grids technologies and the combination of the above with sector coupling of all energy carriers via storage and conversion technologies.
The recent EASE[5] and MIT[6] reports are addressing these challenges for the EU and US respectively.
Energy storage and conversion technologies can provide the necessary flexibility to the energy system across different timescales. Several technologies are available, and their state of the art showed different level of development and maturity. Some of these are established technologies, while others have yet to demonstrate their potential at scale.

Nevertheless, all of them faces challenges that require R&I efforts to be adequate and cost-effective in a carbon-neutral energy system. In line with the objectives of the SET Plan-Action 4 (Statement of Strategic Objectives within an Energy Systems Initiative), the purpose of this paper is to analyse these challenges and propose a set of targets to address them.

Batteries are not included in the analysis, as this is an aspect discussed in Batteries Europe ETIP.

1.2 IP ETIP-SNET WG2

European Technology & Innovation Platforms (ETIPs) have been created by the European Commission in the framework of the new Integrated Roadmap Strategic Energy Technology Plan (SET Plan) by bringing together a multitude of stakeholders and experts from the energy sector. The ETIP Smart Networks for Energy Transition (SNET) role is to guide Research, Development & Innovation (RD&I) to support Europe's energy transition.
In this context this position paper is prepared by the ETIP SNET WG2 (Storage technologies and system flexibilities) to set-out a vision for RD&I for storage technologies and engage stakeholders in this vision.

1.3 Scope of the document

The scope of the document is to provide stakeholders with the data, guidelines, metrics, and analysis to make informed decisions on EU R&I efforts on energy storage technologies. Focus is on performance targets and the metric to track their progresses. Targets will be set to achieve Performance Goals (see dedicated chapter below) in a timeline until 2025 and 2031. The two timelines are set according to the incoming ETIP-SNET new Implementation Plan and Roadmap, respectively ETIP SNET IP 2022-2025 and the ETIP SNET RM 2022-2031. The 2025 timeline intends to provide short terms concrete inputs for the Implementation Plan, while the most looking forward timeline of 2031 intend to support the strategy of the Roadmap.
The set targets will focus on technology development, with an overview of the manufacturing and supply chain, constraints, regulatory barriers and gaps.

1.4 Structure of the document

This position paper will first list the storage and conversion technologies to be analysed with a brief description and their main characteristics. Then, Performance Goals will be introduced and defined to support the analysis and to identify the main challenges those technologies are facing. A mapping exercise is performed to prioritise and optimise the R&I strategy to overcome them. A set of KPIs will be introduced to set targets for the 2025 and 2031 timeframes.
This will be followed by a more detailed analysis of storage and conversion technologies, suggesting, if possible, concrete R&I objectives to improve their performance.

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[1] https://ec.europa.eu/commission/presscorner/detail/en/ip_22_1511
[2] https://ec.europa.eu/energy/sites/ener/files/documents/cleanenergy_com_en.pdf
[3] https://ec.europa.eu/energy/sites/ener/files/documents/cleanenergy_com_en.pdf
[4] https://ec.europa.eu/clima/eu-action/international-action-climate-change/climate-negotiations/paris-agreement_en
[5] Energy Storage Targets 2030 and 2050 Ensuring Europe's Energy Security in a Renewable Energy System – EASE (2022)
[6] The Future of Energy Storage - An Interdisciplinary MIT Study (2022), ISBN: 978-0-578-29263-2

2. STORAGE TECHNOLOGIES

Energy, whether as electricity or as heat from renewable or other forms of generations can be stored and used to decarbonise the energy system. The storage technologies assessed in this paper are then defined by considering the whole system including all the required BOS (Balance of the System) components needed to meet the end-user provisions.
The following technology are analysed in this paper with the exception of battery:

Table 1: Storage and conversion technologies

Type of storage	Type of technology	Description
Electrochemical storage	Battery	Only mentioned. As there is a dedicated ETIP Batteries Europe for this technology, it will be no further analysed
Chemical	P2-Gas-2P	Electricity can be converted into gases to be later used as feedstock for power generation plants (e.g., gas turbines, fuel cells, etc)
	P2-Liquids-2P	Electricity can be converted into liquid fuels (e.g., methanol) to be later used as feedstock for power generation plants
	P2-Gas-2Industry (as gas, to heat)	Electricity can be converted into gases to be later used into industrial facilities as heat sources or process gases
	P2-Liquid-2Industry (as liquid, to heat)	Electricity can be converted into liquid chemicals to be later used into industrial facilities as heat sources or process fluids
	P2-Gas-2Mobility	Electricity can be converted into gases to be later used into light or heavy-duty vehicles as fuel
	P2-Liquid-2Mobility	Electricity can be converted into liquid fuels (e.g., methanol) to be later used into light or heavy-duty vehicles as fuel
	P2-Heat-2P	Electricity can be converted into heat to be later used as feedstock for power generation plants
Thermal	P2-Heat	Electricity can be converted into heat to be used directly as heat sources (e.g. heat pump)
	CSP (Concentrated Solar Power)	Heat generated through concentration of solar light to be used as feedstock for power generation plants or heat source
Mechanical	Flywheels	A kinetic energy storage system composed by a rotating mass, typically axisymmetric, which stores rotary kinetic energy, driven by an electrical machine able to work as a motor or a generator
	Pumped storage hydropower (PSH)	Pumped storage hydropower is based on transfer of water potential energy between two reservoirs.
	Compressed air (CAES)	The CAES technology stores electrical energy in the form of high-pressure air and then generates back electricity through an expansion process when needed.

3. PERFORMANCE GOALS

Energy storage performance goals are here suggested taking as reference the list presented in
the 2020 DOE Roadmap[7]. Performance Goals can be achieved through different storage technology pathways. Their definition is linked to the expected achievement that those storage technologies could offer for a wide spectrum of Use Cases.
The idea is to identify critical performance aspects of energy storage technologies and their possible solutions related to the needs of the identified Use Case, providing metrics to measure this progress through appropriate KPIs.
The following Performance Goals have been selected for the evaluation of different storage technologies:

- **Load response** – able to respond to frequency needs of the grid or user. Here are proposed three classifications of load response:
    - **Short-duration** – able to respond to shifting capacity needs of the grid or user over second or minutes
    - **Mid-duration** – able to respond to shifting capacity needs of the grid or user over the course of a few (1–18) hours
    - **Long-duration** – able to provide services over several days or weeks to meet needs of grid or user
- **Power quality** – provides smooth electricity supply without variations in voltage, frequency, harmonics, unexpected interruptions of any duration, etc.
- **Reliable** – can provide power, even after long inactive periods.
- **Robust** – able to withstand extreme use conditions (mechanical distress, cold temperatures, extreme weather) and not fail.
- **Long lifetime** – able to perform storage services for long time (e.g. in the context of extending storage lifetimes to match renewable power purchase agreements terms until e.g. <20 % capacity degradation).
- **Scalable** – To cost-effectively build large-scale (MW) or small-scale industrial/commercial level.
- **Compact** – has the energy and power density to cost effectively meet requirements for systems with size and weight restrictions.
- **Safe** – Freedom from risk which is not tolerable either in operation or in end-of-life disposal/recycling stages.
- **Efficient** – achieves a high enough conversion efficiency to cost-effectively integrate with necessary energy sources.
- **High material efficiency.** Raw materials requirement in the design, manufacturing, use and end-of-life stages aiming at the reduction of material demand and usage of critical material. Opportunities for a sustainable end-of-life management (remanufacturing, reuse, repurposing and recyclability).
- **Flexible** – able to be easily integrated and operated with existing generation systems and infrastructure (boundary constraints assessment). E.g. The independence from a specific geographical or geological or industrial context.
- **Modular** – can be configured to easily combine other storage systems to achieve precise capacity targets ("plug-and-play"). Support to the decarbonisation of industrial, power production, transport and residential needs.

4. MAPPING METHODOLOGY

The methodology followed to carry out the mapping exercise is based on defining the link between performance goals and use cases and how different storage and conversion technologies could deliver these performances and which metrics (KPIs) to use for tracking them.
For detailed information on the mapping exercise, please refer to the annexes.

4.1 The Use Cases

To reach the required level of decarbonisation by 2050 an extensive electrification in (nearly) all sectors of the energy system is needed. This will rely on a combination of massive use of renewables generation for electricity and heating & cooling as well as energy storage technologies with sector coupling of all energy carriers through conversion technologies (e.g. extensive use of carbon neutral gases and green fuels and possibly hydrogen in industry, transport, and buildings). This scenario designs a series of Use Cases through all sectors of the energy system from the electricity to the gas and liquid fuel network ranging from generation to the final user/costumer, through transmission, distribution, and network assets.

The proposed Use Cases derive from the original classification suggested by EASE EERA[8] in their overview of energy storage applications in the electricity sector. The list differentiates between Generation/Bulk Services, Ancillary Services, Transmission Infrastructure Services, Distribution Infrastructure Services and Customer Energy Management Services. The EASE list has been further updated by the authors of this position paper adding Congestion management and Inertia response/spinning reserve in the Ancillary block.
Congestion management:
It refers to any strategy focused on avoiding, reducing, or eliminating network congestion and/or its negative impact on network performance. Congestion occurs when demand for a resource exceeds that resource's capacity
Inertia response/spinning reserve:
"Frequency-responsive" spinning reserve responds within 10 seconds to maintain system frequency. Spinning reserves are the first type used when shortfalls occur. Inertia is only one of several grid services that help maintain power system reliability. Understanding the role of inertia requires understanding the interplay of inertia and these other services, particularly primary frequency response, which is largely derived from relatively slow-responding mechanical systems.
Then two new blocks have been added for the Thermal and Chemical Services with the respectively Use Cases:
Space Heating and Hot Water Production:

[7] *Energy Storage Roadmap. US Dep Energy Energy Storage Gd Chall. 2020*
[8] *EASE-EERA Energy Storage Technology Development Roadmap 2017 [Internet]. EASE Storage. [cited 25 of February 2022]. Available at: https://ease-storage.eu/publication/ease-eera-energy-storage-technology-development-roadmap-2017/*

Heat is one of major carbon producers in our current energy landscape. Centralisation of heat production creating more efficient distribution system and additionally implementation of waste heat resources (e.g., from industries) is on major trend in several cities. To match supply and demand it is crucial to install balancing assets like (pressurised) hot water reservoirs (e.g. Ruth storage) as well as thermal storages allowing higher temperatures into the networks. This will allow also the implementation of electrification of heat in case of excess power – coupling heat and electricity networks (e.g., via large-scale heat pumps or resistive heating) to enable additional balancing mechanisms.

Heat to Power:

There isn't a cheaper way to store energy then storing energy as heat. The variety of materials capable to store heat is broad (e.g. rocks, salt, steel, concrete,…) and therefore globally available. The major challenge is converting stored heat back to electricity in an efficient way driven by conventional power generation principles, known from steam power plants.

Heat for Industrial processes:

The production of heat for several industries is a key factor for their operations. To decarbonise heat production via integration of renewable energy is a major challenge for our future energy landscape. Using storage assets (either electrical or thermal) and converting renewable power into heat directly at the demand site can be q favourable option to meet our decarbonisation targets while enabling coupling of electricity grid to heat industries, generating additional balancing assets.

Chemical to industrial process:

chemicals like ammonia, hydrogen, methanol and many others can be exploited by existing industrial processes which convert them in the desired final products (for instance, steel or petrochemical products). These "hard to abate" processes would significantly benefit from the green production of the needed chemicals

Chemical to heat:

Similarly to the previous point, green chemicals could also improve the sustainability of heat generation for industrial purposes, since the combustion of such fuels would be basically CO2-free

Chemical to power:

chemicals, both in gaseous and liquid form, could be used to reduce the large carbon footprint of the power production sector. In particular, gaseous chemicals (like hydrogen and biomethane) can be utilised in gas turbines or fuel cells, while liquid chemicals (like methanol and biofuels) can be exploited in cogeneration/power production engines

Chemical to mobility:

another way of exploiting chemicals is to use them instead of traditional fuels to power vehicles. In particular, it can be a very interesting solution for heavy vehicles like trucks, planes, trains and ships, since using batteries would be more problematic. Both gaseous fuels (used in fuel cells) and liquid fuels (Internal Combustion Engines) are considered.

4.2 Importance of Performance Goals to the Use Cases

This first part of the mapping is an attempt to represent how important are the performance aspects of the storage technologies and how may likely be a solution for each Use Case

The scoring ranges from "No Important: 1" to "Highly important: 5" passing through "No important except some situations: 2" and "Very important except some situations: 4", with an intermediate score of 3 and NA=Not Applicable case, when there is no link at all.

4.3 Likelihood to achieve the Performance Goals through specific technologies

The second part of the mapping link the Performance Goals to the specific energy storage and sector coupling conversion technologies.

The question that this exercise seeks to answer is how likely it is that a Performance Goal could be achieved by the specific technology. The mapping will most likely represent the state of the art of the technology, but for the lower scores it also incorporates some level of expectation.

The scoring ranges from "Very Unlikely: 1" to "Highly likely: 5" passing through "Unlikely except some situations: 2" and "likely except some situations: 4", with an intermediate score of 3, NA=Not Applicable case when the technology does not apply. Uncertain score marked with a (?) meaning that more information is required to answer the question.

A low score highlights a challenge that the technology should overcome to make it suitable for achieving the specific Performance Goal. A low score also highlights an opportunity for the technology to improve its performance through R&I actions. Consideration should be provided based on Cost benefit analysis. The comparison of scoring within different technologies should be avoided, since the purpose of the mapping is not to make one technology competing with others, but rather looking for complementarity.

4.4 Relevance of KPIs and metric for the performance Goals assessment

The achievement of Performance Goals must be supported by quantitative, ambitious, and realistic targets. The metrics through which the targets are measured are defined in a set of KPIs.

The following KPIs have been selected:

Table 2: KPIs for energy storage and conversion technologies

KPI	Short description
Lifetime (n. of cycle)	Number of Cycles (Charging followed by Discharging at certain conditions) before the capacity to provide Energy at given Power drop below a given threshold, or until when it is not anymore capable to provide the service as required.
Lifetime (n. of years)	Number of years before the capacity to provide Energy at given Power drop below a given threshold, or until when it is not anymore capable to provide the service as required. It depends on the Duty Cycle foreseen for the storage system and for the P2X-2Y conversions.
Performance (specific power) (W/kg – L – m2)	Power Density (gravimetric, volumetric and in terms of surface).
Performance (specific energy) (Wh/kg – L – m2)	Energy Density (gravimetric, volumetric and in terms of surface).
Efficiency (e.g. Round trip efficiency) (%)	It measures the energy losses in a full cycle. Expressed as ratio of Charged Energy/Discharged energy at the point of connection with the grid or the AC/DC interface, or as the ratio of output energy/input energy in any conversion P2X-2Y.
Safety (e.g. number events and severity)	circumstance in which people, property or the environment is/are exposed to one or more hazards. Hazards is the potential source of harm (injury or damage to the health of people, or damage to property or the environment). Safety is defined as freedom from risk which is not tolerable. Considering the risk as a combination of the probability of occurrence of harm and the severity of that harm, the suggested way to measure safety is to sum up the known events in terms of injury or damage to the health of people, or damage to property or the environment. If possible, make it according to a scale such as the table used for battery cell (EUCAR), but considering also severity for people and environment.
Maturity of technology (TRL-MRL) and dependencies	See: • A technology readiness assessment (TRA) guide. Best Practices for Evaluating the Readiness of Technology for Use in Acquisition Programs and Projects, 2020. U.S. Government Accountability Office (GAO) - https://www.gao.gov/assets/gao-20-48g.pdf; • U.S. Department of Defense Manufacturing Readiness Levels Deskbook (2017); • https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf
Time for deployment (months – years – decades)	Time from project redaction to project execution and commissioning. Several unforeseeable factors could contribute to it such as financing issues and time for approval through the local and national administration. Nevertheless, common patterns could be identified and be enough to provide valuable indication at moths, years and decades scale.
Storing period: hours – days- weeks and self discharge	The charged energy into a storage is kept in the container (such as tanks, vessels, ponds, beds, etc.) for a period until the stored energy is required. Self-discharge refers to internal processes that decrease the capacity of the technology little by little.
short/long/seasonal terms: duration in hours – days- weeks (time to charge, time to discharge)	Storing and discharging periods expressed in Hours - Days- Weeks - Months the system is capable to provide both in terms of energy and power capacity. It may include self-discharging. It is related to the Ratio E/P. Move energy considering time to charge (generic service related to the specific technology: Crate related to E/P) + time discharge (generic service and Crate) + self-discharge (storing periods) Seasonal concept is related to the use case.
Calendar life (months/years)	The period during which the storage remains operational while it is not cycled.

Time response (seconds, minutes)	The time the system requires for the signal sent by the control (local or remote) to be seen at the point of connection - Related to the power electronics and to the media employed by the technology. Time for signal to full load.
Ramp up (W/sec curve)	Ramp up (discharging) W/sec curve (Intermediate value) - Ramp down as charging (of the system) - Partially connected to Time response: Full load/Time response.
Availability (%)	Foreseen downtime (e.g. Maintenance) and unforeseen events downtime over the life of the asset.
CAPEX, OPEX (with exceptions) (Euro/kWh)	Cost in terms of Energy. OPEX is related to the Business case and to the services to be provided. It is usually not included. For the same reason excluded also the LCOE. The cost of energy included in LCOS is also related to use case and local electricity market. Boundary conditions are critical for comparison.
CAPEX, OPEX (with exceptions) (Euro/kW)	Cost in terms of Power. Same consideration as above.
ESOI ratio (%)	Ratio between the Energy Throughput (usually discharged) and the energy invested for its construction.

4.5 Proposed targets timeframe

Targets will be set to achieve Performance Goals in two timelines, until 2025 and 2031. The two timelines are set according to the incoming ETIP-SNET new Implementation Plan and Roadmap, respectively ETIP SNET IP 2022-2025 and the ETIP SNET RM 2022-2031. The 2025 timeline intends to provide short terms concrete inputs for the Implementation Plan, while the most looking forward timeline of 2031 intend to support the strategy of the Roadmap.2025 - ETIP SNET Implementation Plan and 2030 ETIP SNET Roadmap.

5. PUMPED STORAGE HYDROPOWER

5.1 Short description of the technology:

Pumped storage hydropower is based on the transfer of water potential energy. It is composed of two reservoirs at different elevations and an underground Pump Turbine Plant (Figure hereunder).

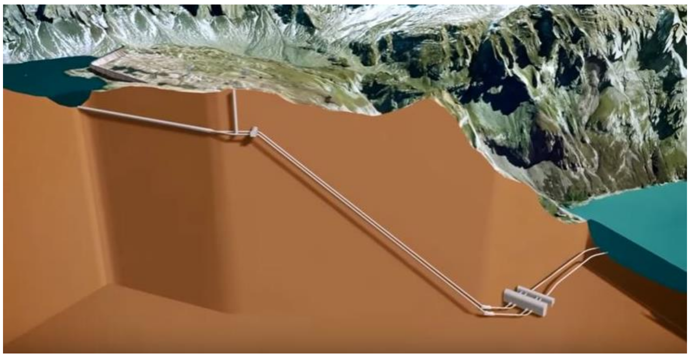


Figure 3: Pumped Storage Hydropower with two reservoirs at different elevations and an underground Pump Turbine Plant

When energy is available on the grid, the pump turbine is in pumping mode, it transfers water from a lower reservoir to a higher one and fills the upper reservoir. When energy is needed on the grid, the pump turbine acts as a turbine, using the potential energy and transfers water from the upper reservoir to the lower one.
The system can operate with different configurations:

- As a complement of classical hydro power plant: one of the two reservoirs is also used to store water for seasonal production while the second reservoir is dimensioned for the use of pumped storage.

- In a closed loop (off river), only water to compensate evaporation had to be added to the system. It is possible to use desalinated water.
- Using cascade of existing reservoirs with addition of a pumped storage plant.

The energy stored is proportional to the size of the reservoir and the head (difference of altitude between the two reservoirs). For example, with two Olympic swimming pools and 500m of head, we can store 3 MWh. As pumped storage plants are generally used for daily or weekly storage, the surfaces of the reservoirs are relatively small.
The environmental impact must be analyzed case by case. It is reduced thanks to the possibility to operate in close loop.

By the end of 2021, 165 GW of pumped storage hydropower were installed worldwide and 55 GW in Europe.
There are several types of pump turbine plants,

- Synchronous plants: These are made up of a pump turbine and a synchronous generator. This represents more than 90% of the existing plants. This technology was developed to compensate the consumption variation. This technology takes into consideration the flexibility required by the intermittent renewable sources.
- Variable speed plants. These are made up of a pump turbine, variable speed generator with power electronics (new technology). Due to the possible variation of the generator speed, additional flexibility is possible, (specifically in pump mode) which represents a great advantage for the grid.
- Ternary group plants. These are made up of one pump, one turbine and sometimes a synchronous generator.

IN THE BEST CASE SCENARIO, the PSH capacity in Europe is expected to reach 72 GW in 2030 with an addition of 17.2 GW from the current 55 GW installed capacity in 2021. This growth is a significant milestone in the sustainable energy sector, and it is estimated that by 2050, the PSH capacity could double or even surpass this number, assuming that any barriers are successfully overcome.

5.2 Challenges (technical and economical) and outlook

Lowest score in PG table at Likelihood to achieve the Performance Goals through specific technologies

Score 3: Flexibility (e.g. The independence from a specific geographical or geological or industrial context)

Implantation of PSH is dependent of local conditions and is generally long

1. Shorten delivery time:

The time for deployment is a challenge: both authorization process and time for construction are long. This is an issue regarding the necessity of energy storage.
The target should aim to reduce lead time from 10 to 5 years with actions on permitting, authorizations and operational lead time:

- The suggestion is to work on acceleration program on the following aspects Accelerate authorization process: work on rule than can speed up the process taking into consideration the limited environmental impact linked to the size and the possibility of operating in closed loop
- Propose a collaborative R&D project to speed up construction time using task parallelization
- Definition of sustainability criteria (IHA/Green Deal) based on consensus conference.
- Long term concessions to facilitate large private investments and launching of large number of projects.

2. Improve long term visibility

A PSH business model is based on long term hypothesis
PSH have a long-life time, a low operational cost and an important initial CAPEX; the lack of visibility on long term energy market is a challenge.
In order to define on long term basis, the most cost efficient and secure solution, we recommend the development of economic model, process and rules that can take into consideration long term needs and grid security.

Score 3: Scalability
In order to improve the deployment of PSH, we suggest

- to identify all the potential site in Europe, including existing reservoir, new reservoir, and marine possibility, to make a classification to define the most interesting one and identify the possibility of creating cluster to accelerate the process through partial standardization
- to improve variable speed technology: Variable speed technology is a strong asset for the grid as it can put large power on the grid in a very short time (lower than second). This technology is new. Research on material, hydraulic development and processes is needed to reduce the cost and the delivery time.

To improve rehabilitation process in order to take advantage of the improvement in term of efficiency and to provide more grid service for ENR integration.

5.3 Advantages and strong position

Highest score in PG table at *Likelihood to achieve the Performance Goals through specific technologies*
PSH provides a good power quality and a very large range of services. The technology is very relevant for the stability of the grid: PSH can provide to the grid large quantity of power in a very short time (few seconds, even milli-seconds for variable speed) and during a long period (hours to week). Black start is possible. Time response is key for the grid management specifically when the quantity of solar is high.

With synchronous machine it is today possible to move from full pump mode to full turbine mode in less than 60s, however R&D should be conducted to decrease the time response further.
PSH is reliable and robust. Its availability: > 95% (96%-98%) thanks to digitalisation of the plant. However, an acceleration plan is needed to improve the operation with more flexibility and to reduce the maintenance cost. This plan can be used for new machine and existing one.
The PSH lifetime is long: the average time before the first refurbishment of the machine is 42 years. Such refurbishment can extend lifetime to over 100 years. However, the operation of the power plant with high level of flexibility requested by the expected increasing share of renewable energy may cause fatigue on the plant and its equipment. To keep the good performance in terms of lifetime the hydraulic design in all operating range should be improved through e.g. improved CFD model, more resistant material, and better forecasting.
In PSH, power and quantity of storage can be chosen independently. Records in term of installed capacity is today Power 3 GW (Bath County; USA) and in term of storage 36 GWh. (Racoon Mountain; USA). Fengning, China (3.6 GW) and Snowy 2.0, Australia (350 GWh) are under construction.
The power density is important and the round-trip efficiency is 75-80%. However, efficiency is an important parameter of the ROI (Return of Investment) and it can be improved. A specific action can be done for the upgrade of existing plant in order to reach 80% of efficiency. For new plants, improvement can reach 82% at the BEST.
The EROI is huge (80-200).
Modularity is possible. There is a strong interest to integrate battery and pumped hydro plants as well as solar (floating solar) in order to provide good electricity quality and high level of grid regulation as well as to decrease machine fatigue. Some projects are existing such as XFLEX HYDRO and the effort should be increased.
The construction of PSH needs mainly concrete and steel, as for hydro power the return of energy is high, and the ratio of used raw material per kWh is low and all are recyclable. There are very few uses of rare materials.

5.4 EU and National R&I projects and pilots

- XFLEX: Hydropower extending Power System Flexibility (funded from Horizon 2020)
- HYDROFLEX
- AFC4Hydro
- ALPHEUS
- HYPOSO
- FITHYDRO

Pumped-storage plants account for about 20% of the total installed hydropower capacity. In 2021 pumped-storage plants in Europe had a generation capacity of about 55 GW and a pump capacity of about 51 GW[9].
Hydropower supplies around 90% of global flexible dispatchable capacity.

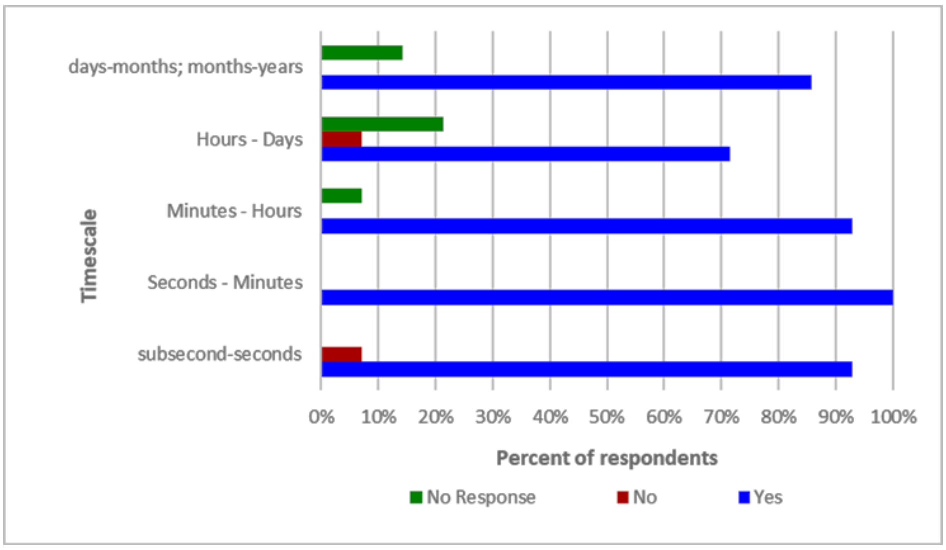
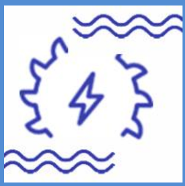


Figure 4: % respondents to the question of whether hydropower provides flexibility services across timescales (IEA, 2021)

[9] 2022 Hydropower Status Report. International Hydropower Association (IHA)

5.5 Proposed target KPI

Table 3: Proposed targets for Pumped Store Hydropower

Performance Goals	Challenges	KPI	Target 2025	Target 2031
				
Scalable: to cost-effectively build large-scale (MW) systems	Large scale is usual, series production is not possible. The problem is each site is unique. The reduction of construction cost is always a target.	TRL investment cost/energy €/kWh	5/6 & 6/7	*Modular small scale PSH solutions.* *(TRL=6/7 & 20-60 €/kWh)* *Competitive marine solutions (TRL=6/7 & 50-100 €/kWh with E>100GWh)* *Development of multipurpose PSH (TRL=5/6 20-30 €/kWh)* *Cost and delivery time reduction on variable speed solutions (TRL=7/8)*
Flexible: (adaptability) able to integrate into infrastructure (boundary constraints assessment)	The most important challenge for hydro storage is the lead time which could be nearly 10 years. Lead time included time for licensing and permitting and time for construction. large environmental compensation participates to that long delivery time.	Time for deployment	5 years	5 years *Innovations on construction technologies.* *Innovative sustainability concept.* *Simplification of procedures.* ***Sustainability criteria approved by European Union** should speed up project acceptance and implementation (TRL=7/8)*
Flexible: (adaptability) able to integrate into infrastructure (boundary constraints assessment)	Largest costs during the construction phase (costs of operation and maintenance are low), which need a long-term vision to establish a business plan.	€/kwh €/kw and TRL	...	*Optimisation of the global system including Long term vision of policy-makers. Long term PPA. Long term concessions* *Integration of ENR (floating PV TRL=8/9)* *Hybridation with Battery to optimise cost, life time and service (TRL=7/8)*

Possible R&I topics:
"Advanced Flexible Hydropower Storage Solutions for Grid Integration and Optimization"
This R&I topic aims to explore innovative approaches in the design and operation of flexible and efficient hydropower storage systems. The focus will be on solutions that are at Technology Readiness Level (TRL) 6-7 and that align with R&I Topic 3.1.1 of the Research & Innovation Agenda of HYDROPOWER EUROPE. The priority for this R&I topic is considered very high and it is recommended that research be initiated before 2025 with a total budget of €26-35 million through several projects.

6. CAES

6.1 Short description of the technology

CAES (Compressed Air Energy Storage) is a relatively mature technology. The D-CAES working concept is derived from gas turbine technology and it stores electrical energy in the form of high-pressure air and then generates back electricity through an expansion process when needed.
There are different technical layouts for a CAES plant. They can be grouped and classified as diabatic (D-CAES), adiabatic (A-CAES) and Isothermal (I-CAES)

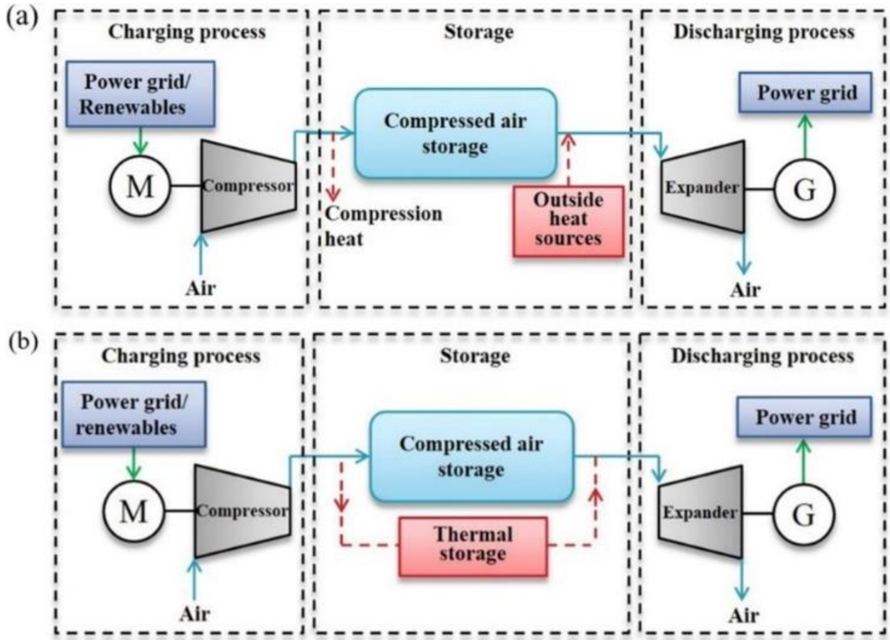


Figure 5: Different types of CAES (a) diabatic D-CAES and (b) adiabatic A-CAES[10]

The diabatic is the traditional CAES plant where the compression heat is rejected to the ambient by appropriate cooling, and fuel combustion is required to heat the compressed air at the inlet of the expander. This results in a quite low cycle efficiency, which is around 40% - 50%. In A-CAES the compression heat is recycled and stored for heating the inlet air of the turbine expander during the discharge process, which optimises the efficiency as well as eliminates dependence on fossil fuels. The cycle efficiency of an A-CAES system can reach 60% – 70%. For I-CAES the thermodynamic of the process is optimised maintaining as much as possible a constant temperature during compression/expansion.[11] For instance, through the injection of a fine, dense mist of water spray to rapidly absorbs the heat energy of compression and uses it in expansion . With I-CAES the expected efficiency could be over 80%.[12]

Currently, in the range of hundreds of MW only three CAES plants are operating in the world: Huntorf Plant in Germany (310 MW), and Mclntosh Plant in the USA (110 MW) which date back respectively to 1978 and 1991[13] and Zhangjiakou in China, a 100 MW A-CAES Plant with overground air-tanks (commissioned in 2020). The first two were originally built to provide black – start services to nuclear plants. Both are D-CAES plants type and they are suffering from low efficiency (respectively with a Round Trip Efficiency of 42 % and 54 %). The last one is an A-CAES-type with a claimed Round Trip Efficiency of >60%.

Many demonstration projects of A-CAES have been proposed such as ADELE in Germany (90 MW, started in 2010), TICC-500 in China (0.5 MW, started in 2014) or the RICAS project in Austria (5 MW, started in 2017). The German and Austrian project seem not active anymore. New projects have been financed and they are under consideration such us the Cheshire Gas in UK (500 MW, due by 2025) and CAES Zuidwending in the Netherlands (320 MW, due by 2024).[14] Both are planning to use as reservoir underground salt caves. A salt cave is also employed by a Canadian pilot plant in Goderich, Ontario with approx. 2MW built by the company Hydrostor.[15] The plant seems to be operative and declared with a cycle efficiency up to 60 %. The company Hydrostor is now bidding for a plant to be built in California, in USA, with an output of 500 MW and capable of storing up to 10 GWh of energy.

There is a growing interest in using underground salt caves for storage operations. However, many regions of the world lack suitable salt deposits, and so, underground reservoir alternatives have been investigated like porous rock formations such as aquifers and natural gas depleted reservoir or old mines. However, several problems have arisen in these test facilities, such us contamination with hydrocarbons, chemical instability of cave layers and difficulties in the sealing of old mines and shafts. Salt caverns offer ideal conditions for compressed air storages because unlike porous reservoirs, the rock salt is inert to oxygen and salt cavern can be artificially made through a solution-mining process.[16]

The CAES technology low efficiency derives not only form the thermodynamic limits and losses in the compression and expansions stages but, especially for isochoric (constant volume) systems, losses can also result from pressure drops for the throttle valve at the exit of the

[10] *Tong Z, Cheng Z, Tong S. A review on the development of compressed air energy storage in China: Technical and economic challenges to commercialization. Renew Sustain Energy Rev. 1 de enero de 2021;135:110178.*

[11] *Qin C, Loth E. Simulation of spray direct injection for compressed air energy storage. Appl Therm Eng. 25 de febrero de 2016;95:24-34.*

[12] *Tong Z, Cheng Z, Tong S. A review on the development of compressed air energy storage in China: Technical and economic challenges to commercialization. Renew Sustain Energy Rev. 1 de enero de 2021;135:110178.*

[13] *Chen H, Peng Y hang, Wang Y ling, Zhang J. Thermodynamic analysis of an open type isothermal compressed air energy storage system based on hydraulic pump/turbine and spray cooling. Energy Convers Manag. 15 de enero de 2020;204:112293.*

14 https://corre.energy/projects/

15 https://qz.com/1711536/canadian-startup-hydrostor-is-storing-energy-in-compressed-air/#:~:text=Compared%20to%20lithium%2Dion%20batteries,an%20efficiency%20closer%20to%2040%25)

*16 * Evans D, Parkes D, Dooner M, Williamson P, Williams J, Busby J, et al. Salt Cavern Exergy Storage Capacity Potential of UK Massively Bedded Halites, Using Compressed Air Energy Storage (CAES). Appl Sci. enero de 2021;11(11):4728.*

** D7.1 Conceptual design of a salt cavern or porous media storage site - Histories project [Internet]. Hystories. [citado 15 de marzo de 2022]. Disponible en: https://hystories.eu/publications-hystories/*

** Habibi R. An investigation into design concepts, design methods and stability criteria of salt caverns. Oil Gas Sci Technol D'IFP Energ Nouv. 2019;74:14.*

** Gillhaus A, Horvath PL. Compilation of geological and geotechnical data of worldwide domal salt deposits and domal salt cavern fields. Solut Min Res Insitute KBB Undergr Technol GmbH Clarks Summit PA USA. 2008;*

cave.[17] The heat management associated with CAES are also affecting the overall performance of A- and I- CAES systems. The heat generated from compressed air must be well managed through the inter stages heat exchangers as well as sensible heat storage. Performance can be improved if pressure inside the cave is maintained constant through the charging-discharging cycle: it allows machinery to operate at design-point (usually high-pressure point). The isobaric (constant pressure) solution proposed by the Canadians company Hidrostor is to use water connected via pipes to a surface-level reservoir to balance the air pressure inside the underground cavern. When compressed air fills the cavern, it pushes the water through the pipe and up to the ground. The process is reversed when the compressed air is used to produce power. However, the question for isobaric storage is whether the increase in the performance compensates for the increased complexity in the high-pressure storage design.

The passage from big scale CAES plant to relatively small CAES plant is usually set at 100 MW, at which point the profitability of over ground tanks/cylinders became unviable if discharge duration exceeds few hours. These non-geological CAES schemes with over ground tanks/cylinders can only offer storages of small volume. Nevertheless, there is a trend for developing smaller CAES systems integrating CAES technology to a cogeneration system or making the CAES system itself operating as a cogeneration system[18] for residential applications as well as in industrial symbiosis context (see the plant of Zhangjiakou, mentioned above).

The I-CAES is still far for being demonstrate at pilot level. Reversible near-isothermal compression and expansion would remove the need for high temperature thermal storage improving substantially the overall efficiency. However, isothermal compressors and expanders are still at very low TRL and have not been demonstrated at scale.

Although most components in the CAES system are quite common in industrial environment, compressors, turbines, thermal exchanger and thermal storages equipment cannot be simply acquired “off-the-shelf”. To be used in CAES systems the constituent components present many crucial differences with their counterparts developed for typical industrial applications. In addition to that, the integration of heat-storages (for A-CAES) in transient operation modes introduce further technological challenges and need research effort. Therefore, also refer to Thermal storage section below.

Hydrostor claims that a 250 MW power A-CAES system with 2,000 MWh of energy storage capacity (that is, providing 8 hours of electricity) costs about $440 million. It comes out to approximately $220/kWh.

Similar figures are provided by the Corre Energy promoter of the project in Zuidwending in The Netherlands with a 320 MW power A-CAES system with 1,92 GWh (6 hours discharging capacity) with a CAPEX of about 350 M€ (182 €/kWh).

In the analysis performed by DOE (USA)[19] CAPEX cost estimation ranges from approximately $300/kWh for 100 MW and 4 hours systems down

to $120/kWh and 10 hour system. In the same study Fixed and Variable O&M CAES costs are also estimates by power capacity (2020 values) (see table below)

Table 4: Cost estimation for CAES systems

Component	100 MW System	1,000 MW System	10,000 MW System
Full-time staff	2	4	8
Total labor cost ($M)	$600,000	$1,200,000	$4,800,000
Labor-related fixed O&M ($/kW-year)	6	1.2	0.48
Maintenance-related fixed O&M ($/kW-year)	10.30	10.30	10.30
Total fixed O&M ($/kW-year)	16.30	11.50	10.78
Total variable O&M ($/MWh)	0.5125	0.5125	0.5125

The CAES technology is generally considered to have a negligible environmental impact. Nevertheless, in case of CAES with underground reservoir a special attention should be dedicated to the assessment of potential impact on groundwater and prevent contamination to

17 Zhang S, Wang H, Li R, Li C, Hou F, Ben Y. Thermodynamic analysis of cavern and throttle valve in large-scale compressed air energy storage system. Energy Convers Manag. 1 de marzo de 2019;183:721-31.

18 Vieira FS, Balestieri JAP, Matelli JA. Applications of compressed air energy storage in cogeneration systems. Energy. 1 de enero de 2021;214:118904.

19 Mongird K, Viswanathan V, Alam J, Vartanian C, Sprenkle V, Baxter R. 2020 Grid Energy Storage Technology Cost and Performance Assessment. 2020;117.

local aquifers both in the construction, operation and decommissioning phase.[20]
The main safety concern reported for CAES plants, besides the usual industrial hazards, is the risk of fire derived from the possible presence of combustible gases in the underground caves. Before filling the underground formation with compressed air, it is important to purge the area to remove all the natural and inflammable gases that may be present. This will help significantly to reduce or remove any of the hydrocarbons that are present, mitigating the risk of fire.[21]
The chance of reaching high market maturity in 2030-2031 in the European energy scenario is not very high, especially for >100 MW underground plants. Due to the lack of data and the small number of ongoing projects, it is not possible to estimate what the market share of CAES technology in energy storage could be by 2030 IN THE BEST CASE SCENARIO.

6.2 Challenges (technical and economical) and outlook

Lowest score in PG table at Likelihood to achieve the Performance Goals through specific technologies

Score 3: Load response – Mid duration (1-18 hours)
For the CAES technology, the main contribution to the CAPEX is coming from the power figure. This is especially true for large scale CAES > 100 MW with underground reservoir. Once the plant has been designed for a given power, to increase the duration requires a bigger underground reservoir. However, to reach 18-24 hours duration the size and characteristic of the required underground cave are not yet fully explored. This require a deeper geological knowledge of the most suitable sites, especially for salt caves which can be man-made through a solution-mining process. Several works and project are running in parallel in the context of H2 storage and a complementary assessment for CAES applications is recommended.
Score 2: Load response – Long duration (days - weeks)
To reach several days duration the CAES would require a very big underground reservoir. According to the DOE[22], the largest known existing cavern in USA has a volume of 2,7 million of m3, which corresponds to about 64,000 MWh of storage (close to 1 week discharge duration for a 500 MW CAES plant). The Bethel Energy Center cavern can be expanded to 1,6 million of m3, while ATMOS Energy is developing a 1,6 million of m3 cavern on the west of the existing Bethel dome, corresponding to nearly 40,000 MWh of storage. As demand for long-term storage increases, it is expected that caverns of similar size should be developed. However, such sizes could become available only in very few locations in the world.
Score 3: Scalability
The passage from relatively small CAES plant to big scale CAES plant is usually set at 100 MW, from where the profitability of over ground tanks/cylinders became unviable if exceeding few hours of discharge duration. Existing and planned large scale commercial and pilot plants size are ranging from 100 to 500 MW. At such levels, multistage compression/expansion processes are required, and the construction of such big equipment require a big R&I effort to make the overall cycle thermodynamic close the ideal one and reducing the losses. Although increasing the numbers of air compression and expansion stages is an effective way for improving the efficiencies getting the system to work close to the ideal conditions, higher numbers of stages of air compression and expansion normally means more complexity of the whole system, which can affect the system reliability and stability in practice.

Although non-geological CAES schemes with over ground tanks/cylinders can only offer storages of small volume, the integration with cogeneration system or making the CAES system itself operating as a cogeneration system for residential applications as well as in industrial symbiosis context is an interesting option to be assessed and evaluated. The constituent components of CAES systems present many crucial differences with their counterparts developed for typical industrial applications. To be used and appropriately scale-up novel design and R&I approaches are required.
The scalability performance goal is strictly related to the efficiency performance goal.
Score 2: Efficiency
The CAES technology main drawbacks is efficiency.
A-CAES are improving the RTE with respect to D-CAES, but still very few pilot plants are operative. Isobaric A-CAES air storage is a promising option for mitigating many of the losses associated with isochoric A-CAES. Although this would certainly increase the engineering complexity of the High-Pressure store, the difficulties of variable pressure operation make further research on isobaric systems worthwhile.
Isothermal I-CAES promise a substantially improvement of the efficiency, but I-CAES is still far for being demonstrate at pilot level.
The regulation of the CAES charging time and discharging time via flow control can also lead to different system efficiencies, as well as the associated thermal storages and exchangers.
Score 3: Flexibility
Large scale CAES technology (> 100 MW) is limited by the scarce availability of underground reservoir.
Linked to the Load response
Time for deployment may become an issue considering the time to spend on the geological assessment and preparation of the underground caves

20 Final Environmental Assessment For The Pacific Gas And Electric Company (Pg&E) Compressed Air Energy Storage (CAES) Compression Testing Phase Project, San Joaquin County, California. DOE; 2014.
21 Olabi AG, Wilberforce T, Ramadan M, Abdelkareem MA, Alami AH. Compressed air energy storage systems: Components and operating parameters – A review. J Energy Storage. 1st february 2021;34:102000
22 Mongird K, Viswanathan V, Alam J, Vartanian C, Sprenkle V, Baxter R. 2020 Grid Energy Storage Technology Cost and Performance Assessment. 2020;117.

6.3 Advantages and strong position

Highest score in PG table at Likelihood to achieve the Performance Goals through specific technologies

The CAES storage system uses established and mature technologies. This gives the CAES system good reliability and robustness. For CAES technology, safety is not a major concern and most of the material used in CAES installation is mainly steel and concrete, materials with a relatively high end-of-life management efficiency. The expected lifetime is also relatively high, at least looking at the existing running facilities such as the Huntorf Plant in Germany (1978), and McIntosh Plant in the USA (1991).

6.4 EU and National R&I projects and pilots

- https://correenergystorage.nl/caes/
- https://www.durham.ac.uk/news-events/latest-news/2022/02/off-shore-energy-storage-project-wins-uk-government-backing/;
- https://www.crondall-energy.com/post/innovation-in-compressed-air-energy-storage

6.5 Proposed target KPI

Table 5: Proposed targets for CAES technology

Performance Goals 	Challenges	KPI	Target 2025	Target 2031
Load response – Mid duration (1-18 hours)	For CAES > 100 MW, once the plant has been designed for a given power, to increase the duration requires a bigger underground reservoir. However, to reach 18-24 hours duration the size and characteristic of the required underground cave are not yet fully explored. This requires a deeper geological knowledge of the most suitable sites.	Duration in hours (time to charge, time to discharge)	CAES > 100 MW - 10 hours	CAES > 100 MW - 18 hours
Scalable: to cost-effectively build large scale systems	Existing and planned large scale commercial and pilot plants size are ranging from 100 to 500 MW. At such levels, multistage compression/expansion processes are required, and the construction of such big equipment require a big R&I effort to make the overall cycle thermodynamic close the ideal one and reducing the losses.	Maturity of technology (TRL-MRL) and dependencies CAPEX €/kWh	*500 MW plants: up to TRL 8 CAPEX < 200 €/kWh*	*1 GW plants: up to TRL8 CAPEX < 250 €/kWh*
Scalable: to cost-effectively build relatively small scale systems in industrial symbiosis	Non-geological CAES schemes with over ground tanks/cylinders can only offer storages of small volume but the integration with cogeneration system is an option to be assessed and evaluated		*<100 MW plants; Cogeneration: up to TRL 8 CAPEX < 150 €/kWh*	*<100 MW plants; Cogeneration: up to TRL9 CAPEX < 150 €/kWh*
Efficient: high enough conversion efficiency to cost-effectively integrate with necessary energy sources	The CAES technology main drawbacks is efficiency. A-CAES, Isobaric A-CAES, I-CAES and air and heat flow regulation require deeper understanding of thermodynamics and operational limits	Round trip efficiency: %	*70 %*	*85 %*

Flexible: able to integrate into infrastructure (boundary constraints assessment)	Large scale CAES technology (> 100 MW) is limited by the scarce availability of underground reservoir. Time for deployment may become an issue considering the time to spend on the geological assessment and preparation of the underground caves	-Maturity of technology (TRL-MRL) and dependencies -Time for deployment	• ? • *?* *(There is not enough data available to make an assessment)*	• ? • *?* *(There is not enough data available to make an assessment)*

Possible R&I topics:

- Develop a A-CAES or I-CAES over ground tanks/cylinders pilot plant with efficiency above 75% considering cogeneration and thermal storage options for industrial applications (Up to TRL7).
- Evaluate the potentiality of large scale CAES technology (> 100 MW) looking at availability and feasibility of underground reservoir (Up to TRL 7). Develop methodology to speed-up geological assessment and preparation of the underground caves.

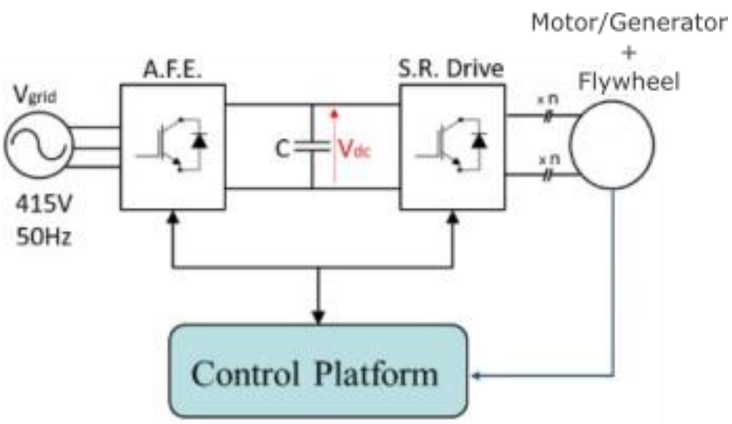
7. FLYWHEELS

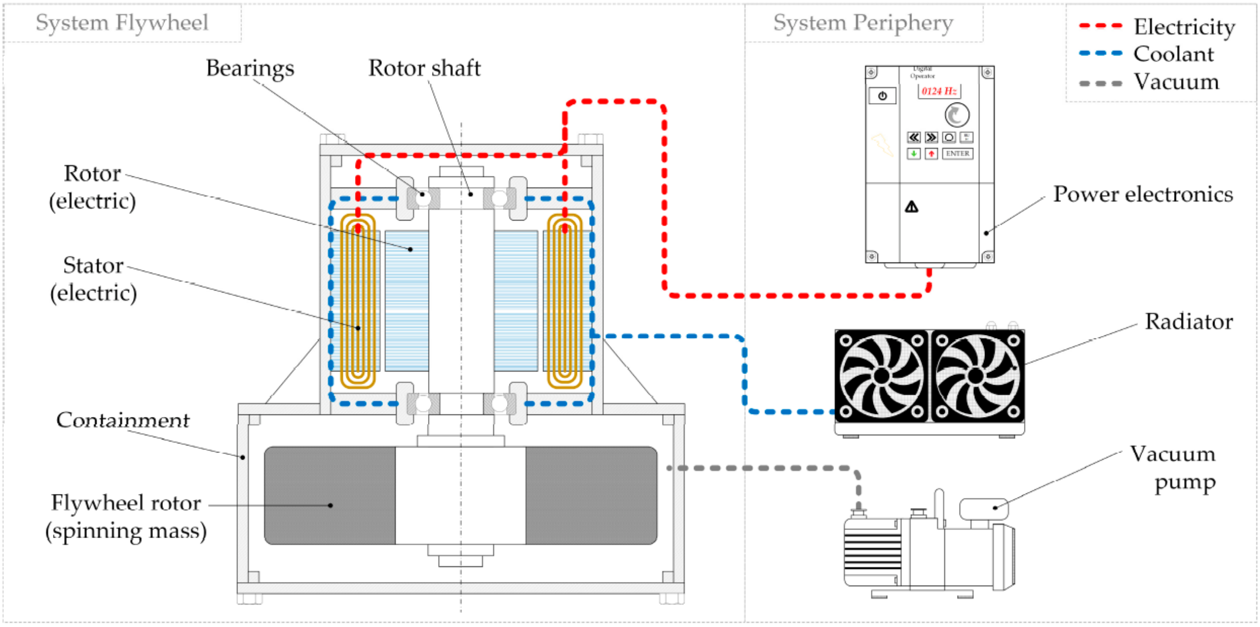
7.1 Short description of the technology

The main components of a flywheel system are shown schematically by the simplified diagram of Figure 10. The system comprises of an Active Front End (AFE) converter, made up of a 3-phase Voltage Source Inverter (VSI), which provides bi-directional power flow between the external, three-phase grid and the DC voltage side (Figure 2a). At the other side of the DC voltage side stands the electric motor/generator, a variable-speed electric drive, whose rotor is mechanically connected to the flywheel itself, as illustrated in Figure 2b. In the basic control scheme, the AFE is tasked with DC-link voltage control, whereas the SR Drive controls the rotational speed, i.e., energy stored, and the rate of charging/discharging. The AFE will thus export/import energy from the grid in accordance with the DC-voltage fluctuations, these last being caused by the flywheel charging/discharging, i.e., accelerating/decelerating.

On the other hand, due to the several technological bottlenecks discussed in the following subsections, flywheels remain a niche technology, used only in a very limited number of industrial applications. Hence, as this technology stands at the moment, chances of reaching a high market maturity in 2030-2031 in the European energy scenario remain extremely low, especially for >10 MW plants. Moreover, due to the lack of data and the small number of ongoing industrial projects, it is not possible to estimate the expected market share of flywheels in the future energy storage pool by 2030, even IN THE BEST CASE SCENARIO.

Figure 6: Flywheel energy storage, system-level illustration (a) and flywheel + motor/generator system (b)





7.2 Challenges (technical and economical) and outlook

Lowest score in PG table at Likelihood to achieve the Performance Goals through specific technologies

Score 1: Load response (mid duration – hours range)

Flywheels nowadays are effectively employed in all kinds of applications requiring short-term power management, pulsed power and very high frequency charge/discharge cycles. Flywheels usually provide load responses of around 10 minutes, although a recent pilot prototype designed for 4 hours spun off in Hawaii by Amber Kinetics.[23]

A way to achieve a higher energy capacity is to minimise idling losses. Here, the two main solutions needed to minimise both friction and drag effects are respectively: 1) magnetic bearings and 2) deep-vacuum operation. Both technologies would require further R&I efforts in a bid of reducing their costs. However, bearing in mind that flywheels are mostly suited to short-duration, high-cycle applications[24], investments in this field might not be a strict priority.

Score 2: Scalable – to cost-effectively build large-scale (e.g. MW) systems.

The limited number of applications flywheels are ideally suited for is possibly constrained by the low number of investments received. This kept its maturity levels not so high, as well as costs not so low.

The main limitation in scalability is due to the need of mitigating the considerable safety issues that flywheels pose. In fact, most of the infrastructure volume and cost is currently devoted to bunkering any single flywheel unit, with the additional inconvenience of maintaining a specific safety distance to avoid domino effects.

Eventually, the capacity to intervene on costs and TRL and MRL levels in EU is also depending on how much of the manufacturing and supply chain industry for the flywheels is present in Europe (https://www.maximizemarketresearch.com/market-report/flywheel-energy-storage-system-market/122077/).

Score 2: Safety

Nowadays, flywheels have in safety issues their most critical bottleneck, which is probably the main barrier to their large-scale deployment. Indeed, consequences of flywheel failures can be literally catastrophic [25,26] . Consequently, current state-of-the-art flywheels require an installation in underground, concrete-reinforced bunkers, which dramatically increases both installation costs and footprint.

Hence, a key point where R&I activities are needed is definitely safety. Indeed, the development of flywheel units with the current rates of power and energy but not requiring a bunkering system could dramatically change the impact of this technology.

For example, a possibility to reduce the current safety issues is being studied, based on a laminated rotor structure.[27]

Score 3: Efficiency

Flywheel efficiency issues are mostly related to idling losses. Therefore, all comments provided in the load response subsection apply here.

Score 3: Flexibility

For what is concerned with flexibility, i.e., ability to integrate into infrastructure, the main bottleneck remains the necessity of bunker installations, which, in turn, is tightly bonded to the safety issues mentioned above.

Score 3: Transportation

Literature provides several examples of how flywheels could considerably help the transportation sector, mostly in two areas:

- Stabilising and aiding fast chargers of EVs.
- Recovery breaking energies in railways or tramways (installation can be either in-station or on-board).

These applications would require flywheels to be installed in the vicinity of people, in locations that usually do not permit the realisation of

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[23] *https://pv-magazine-usa.com/2018/03/14/pilot-project-for-flywheel-storage-underway-in-hawaii/*
[24] *Pullen KR. The Status and Future of Flywheel Energy Storage. Joule. 19 of June de 2019;3(6):1394-9.*
[25] *https://www.kpbs.org/news/public-safety/2015/06/10/explosion-quantum-energy-poway/*
[26] *https://eastwickpress.com/news/2011/07/a-mishap-at-the-beacon-power-frequency-flywheel-plant/*
[27] *https://www.leadingedgeonly.com/innovation/view/flywheel-energy-storage/*

bunkers. Consequently, safety concerns remain once again the main bottleneck.

7.3 Advantages and strong position

In summary, flywheels excel in short duration and high cycle applications, and another measure of value is the cost for a given total energy throughput, virtually unlimited because of a high cycle life.
Overall, PGs where flywheels score highest are the following:

- Load response – Short -duration (second - minutes), see above.
- Power quality: provides smooth electricity supply. A DC-link bus and an inverter are always available to the grid for any exchange of reactive power.
- Robust: able to withstand extreme use conditions (e.g temperature) All flywheel components are practically temperature and pressure insensitive, making them very suitable for harsh environments.
- Long lifetime. Most manufacturers declare a 25-year lifespan.
- High material efficiency and sustainable end of life management. Almost all flywheels material is fully recyclable, except some semi-conductors' parts of the power electronics converter.

7.4 EU and National R&I projects and pilots

- Flywheel energy storage for wind power generation (FP4-NNE-JOULE C).
- AdD HyStor (Horizon 2020).
- Electric vehicle charging and energy storage system (EVC-EES) to combine electrification of transport to global electricity access in a rural area of Rwanda connected to a mini-grid (Innovate UK).
- https://www.leclanche.com/leclanche-completes-second-hybrid-energy-storage-system-with-s4-energy/ Hybridization of flywheel storage with battery storage to provide primary control power for frequency stabilization in North Holland.
- https://levistor.com/#key (EV fast charging infrastructure).

7.5 Proposed target KPI

As discussed above, the most urgent countermeasures aimed at fostering innovative flywheel solutions are needed in safety. Here, it is relatively complex to define a specific yet measurable KPI, especially because of the relatively low number of commercial models of flywheels.
However, a possible target could be defined as follows: "Keeping the current values of power and energies with flywheel units that do not require concrete-reinforced bunkers".

Table 6: Proposed target for Flywheel technology

Performance Goals 	**Challenges**	**KPI**	**Target 2025**	**Target 2031**
Safe	The most urgent countermeasures aimed at fostering innovative flywheel solutions are needed in safety. The development of flywheel units with the current rates of power and energy but not requiring a bunkering system could dramatically change the impact of this technology.	• Safety (e.g. number events and severity)	• It is relatively complex to define a specific yet measurable KPI. Very limited information on accident especially because of the relatively low number of commercial models of flywheels. *(As safety stands as the main bottleneck, its quantification remains a hard task to accomplish;*	• It is relatively complex to define a specific yet measurable KPI. Very limited information on accident especially because of the relatively low number of commercial models of flywheels. *(As safety stands as the main bottleneck, its quantification remains a hard task to accomplish;*

			hence, the same applies to the assignment of a specific TRL)	*hence, the same applies to the assignment of a specific TRL)*

As per future R&I projects, a couple of possible topics are as follows:

- Develop a single or a modular flywheel unit that does not need an in-bunker installation, and whose post-failure consequences do not put persons' lives at risk. Energy and power density shall remain the same as those currently reached excluding bunkers' bulks (Up to TRL7).
- Develop a single or a modular flywheel unit suitable for energy recovery of trains, trams or metros, bearing in mind that compactness and safety level must both be sufficient for installations inside or nearby passengers' stations (Up to TRL7).

8. ELECTRIC

8.1 Short description of the technology

Conventional capacitors store electrical energy electrostatically by physically separating opposite charges, with no chemical or phase changes taking place. This process is highly reversible and the charge-discharge cycle can be repeated almost indefinitely. Electrochemical capacitors, also referred as "supercapacitors" store electrical charge in an electric double layer at the interface between a high-surface-area carbon electrode and a liquid electrolyte. Consequently, they are also quite properly referred to as Electric Double Layer Capacitors (EDLC).

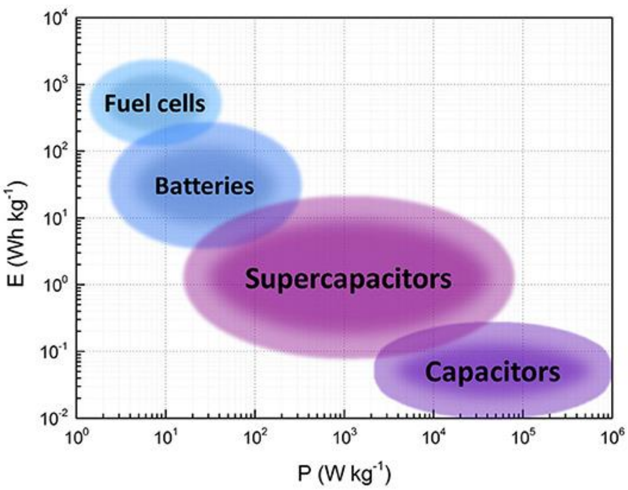


Figure 7: Ragone plot showing the typical values of energy and power of different energy storage devices (Inamuddin et al., 2018)[28]

Supercapacitors are a special class of electrochemical energy storage that have the ability to withstand a very high number of charging/discharging cycles with very low impact on the aging of the material. Unlike other types of electrochemical energy storage (such as batteries) which would wear out after being cycled as result of numerous chemical reactions, the lifetime of this technology seems not being significantly impacted by the number of cycles that is subject to.
Structurally, the electrodes are often made of carbon nanotubes, which, under a microscope appear as masses of twisted strings. This considerably increases the surface area of the electrodes, increasing the storage capacity of these devices significantly. In some devices, every square centimetre of electrode consists of one to two thousand square meters of surface area-this significantly increases the capacitance, and thus energy storage capacity of the device over conventional capacitors.

[28] *Inamuddin, Ahmer, M. F., Asiri, A. M., and Zaidi, S. (2018). Electrochemical Capacitors: Theory, Materials and Applications. Millersville, PA: MaterialsResearch Forum LLC.*

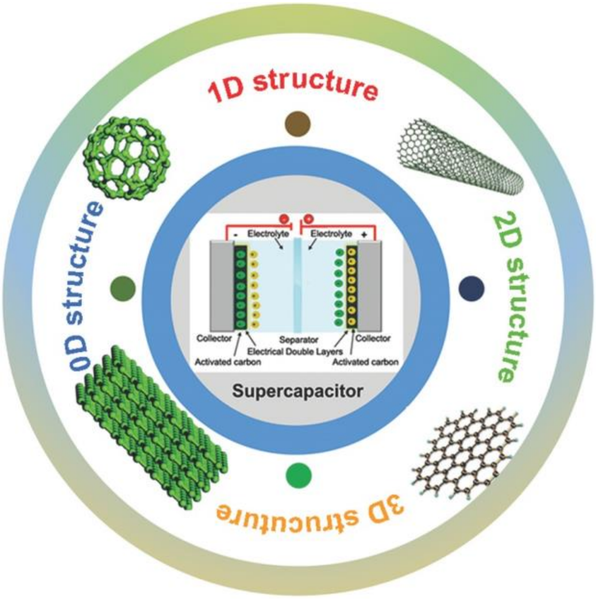


Figure 8: Progress of Nanostructure Electrode Materials for Supercapacitors[29]

Electrode surface area in capacitors determines the capacitance and thus, the energy storage capability of the device. The amount of energy stored by supercapacitors is very large compared to a standard capacitor because of the enormous surface area created by the porous carbon electrodes and the very small charge separation created in the double layer.

The most recent supercapacitors' designs are asymmetric and hybrid and comprised of two capacitors in series, respectively, two electrodes with the same active material but with different mass and capacity loadings, and one capacitor-like electrode and the other a battery-like, with varying electrode capacity ratios, depending on the application. The battery-like or pseudocapacitor electrode relies on highly-reversible redox (electron charge transfer) reactions.

In this design, the capacity of the battery-like electrode is generally many times greater than the capacity of the double layer capacitor electrode, which is the basis for the name "asymmetric or even hybrid". In practice, the variable combination of these materials, electrodes and novel electrolytes has created a variety of alternatives and designs not easily identifiable.

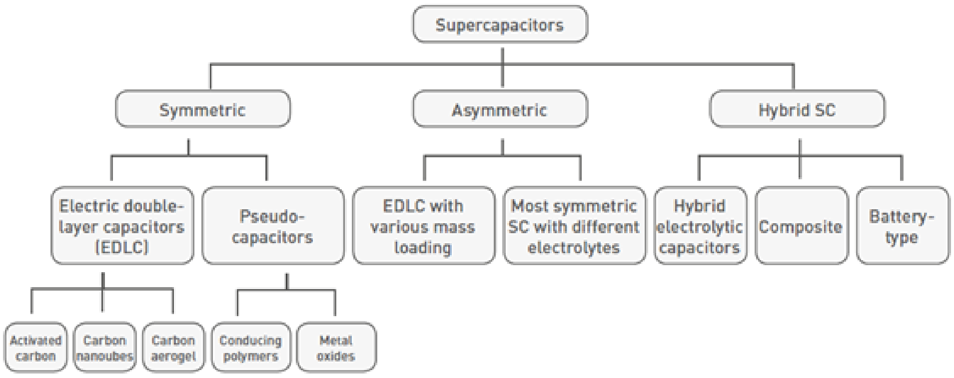


Figure 9: Variety of alternatives and designs for Supercapacitor technology

More recently, supercapacitors have gained more relevance as an alternative form of energy storage as result of their high-power density, fast response and long-life cycle. Although supercapacitors are comparable to lead-acid batteries in terms of energy density and cost, they show considerably more cycling capacity and superior performance at low temperatures. These capabilities turn this technology suited to the provision of fast response system services, such as voltage control.

In terms of demonstration projects, the STORE project (Canary Island, Spain) and recent H2020 project OSMOSE, envisages the use of hybrid systems comprising supercapacitors for power system support, including inertia emulation, frequency regulation and voltage control.

[29] *Jiang et al, Progress of Nanostructured Electrode Materials for Supercapacitors, Advanced Sustainable Systems, Vol. 2, Issue 1, January 2018*

8.2 Challenges (technical and economical) and outlook

Lowest score in PG table at Likelihood to achieve the Performance Goals through specific technologies.

Supercapacitors are interesting for their power density, high life time and capacity to withstand high ramps. The storage system round-trip efficiency is extremely high, around 95%.
The low energy density and high capital costs (estimated in the range of 1100-2000 €/kW, including installation costs) limit the use of supercapacitors in electricity grids to high-power applications (up to 10 MW) with growing interest from electric utilities, which are looking to these devices for performance improvement and reliability in a variety of areas, with much higher power levels and with distribution voltages up to 600 V.
Score 1: Load response (Mid/long duration – several hours / days range)
Supercapacitors are being effectively employed in short-term applications requiring fast response and low energy requirements, which requires a high number of charge/discharge cycles. The response time of supercapacitors stays within the ms range and usually are capable of providing responses between several seconds to few minutes. A way that is being pursued to achieve a higher energy capacity is through the development of new materials. However, these processes take normally several years and are subject to a high level of uncertainty regarding the end results.
Score 3: Compact – Cost-effective improved Energy & Power density.
Supercapacitors have a relatively high power to weight ratio (0.5-5 kW/kg). This is achieved as result of the large specific surface area of the electrodes which can reach 1966 F/g.[30] Development of promising new materials, such as carbon nanotubes (CNT) and polymer composites, holds the potential for achieving even higher power density, expanding the potentialities and applications of this technology.
Score 3: Support to the decarbonisation of industrial, power production, transport and residential needs
The ability of supercapacitors to support the decarbonisation of the power sector is still restricted to few opportunities, mostly as consequence of the very limited energy density of this technology. Progress made in the expansion of the energy density of this technology could revolutionise the supercapacitors' applications. At the time, the integration of supercapacitors in hybrid flexibility solutions can provide more complete solutions, by taking advantage of the characteristics of this technology when combined with others that are more energy proned.

8.3 Advantages and strong position

Highest score in PG table at Likelihood to achieve the Performance Goals through specific technologies
Resuming, supercapacitors have a very high performance in short duration, high power and high cycle applications.
Overall, PGs where supercapacitors score highest are the following:

- Load response – Short -duration (second - minutes), see above.
- Power quality: provides smooth electricity supply. The very fast response and virtually unlimited cycling capability makes this a very suitable solution.
- Long lifetime. Most manufacturers declare a 10-20-year lifespan (over 500 000 cycles).
  Supercapacitors' material is subject to strict recycling rules as defined in the WEEE Directive (2012/19/EU).
- Flexibility & Modularity. Supercapacitors are easily combined with other flexibility options (e.g electrochemical storage) contributing in the power support of the overall solution.

8.4 EU and National R&I projects and pilots

Supercapacitors have been targeted in several projects and pilots, including:

1. **H2020 project, OSMOSE (GA # 773406)**, WP4 demo – Multiple services provided by the coordinated control of different storage and facts devices, in which a hybrid system comprising a 4 Mvar STATCOM, 0.8 MW supercapacitor and a 2MW/0.5 MWh Li.ion battery were deployed for the provision of multiple system services, including inertia emulation, fast fault current injection, power oscillation damping, frequency regulation, setpoint tracking, RES capacity firming, congestion management and voltage control.
2. **H2020 project, HyFlow (GA # 963550)**, Modern energy grids are smart and rely on fluctuation of the renewable energies sources, e.g. solar power, and are characterised by higher fluctuations in both power generation and energy consumption. In order to absorb resulting power peaks and to cope with the increased demand for renewable energies, modern grids need more dynamic storage systems. Hybrid energy storage systems (HESS) with high-power redox flow batteries and supercapacitors working as a team are uniquely suited to provide multiple system services at low cost and without the use of critical resources.
3. **H2020 project, CareSTOR (GA # 730798)**, The CareSTOR project aims at the scale-up, techno-economic assessment and commercialisation of unprecedented nanoporous carbons (NPCs) and the Supercapacitor cells and modules (stacks of cells) implementing this material (CareCAPs). NPCs outperform commercial competitors by as much as 40-50% in terms of energy storage per gram of material, adding some promising indicators in terms of volumetric storage as well.

[30] *S. H. Nagarajarao et al., "Recent Developments in Supercapacitor Electrodes: A Mini Review," ChemEngineering, vol. 6, no. 1, p. 5, Jan. 2022, doi: 10.3390/chemengineering6010005.*

8.5 Proposed target KPI

The most relevant limitation to overcome is the low energy density of supercapacitors. An increase of this KPI in the order of 40 to 50 % could be a game changer.

Table 7: Proposed target for Supercapacitors

Performance Goals 	**Challenges**	**KPI**	**Target 2025**	**Target 2031**
Load response – Mid duration (1-18 hours)	For MW scale supercapacitors is challenging to go beyond several minutes.	• Duration in hours (time to charge, time to discharge)	• Supercapacitors > 1 MW – up to 1 hour	• Supercapacitors > 1 MW up to 6 hours
Compact: Cost-effective improved Energy & Power density	The low energy density of Supercapacitors systems is the most prominent barrier for the cost-effectiveness of this technology, when compared with other alternatives available.	• Maturity of technology (TRL-MRL) and dependencies • CAPEX €/kWh	• *0.5- 1 MWh scale plants up to TRL 7-8* • *CAPEX < 3000 €/kWh*	• *0.5 MWh scale plants up to TRL 8-9* • *CAPEX < 600 €/kWh*

9. ELECTROMAGNETICAL

9.1 Short description of the technology

Superconducting Magnetic Energy Storage (SMES) is a form of electrical energy storage, which resorts to the dual nature of electromagnetism. The operation of SMES systems consists of storing energy in a magnetic field created by the flow of direct current in a superconducting coil. An electrical current in a coil creates a magnetic field and the changes of this magnetic field create an electrical field. The magnetic flux is the reservoir of energy. Superconducting wires do suffer from Joule effect (losses) when conducting a current, so the coil made with these materials is able to maintain the current and the magnetic flux stored. The current continues to loop around the coil indefinitely until it is needed and discharged. As a reference, a cubic meter of magnetic flux with a density of 10 T has an equivalent energy of 40 MJ (11 kWh), roughly the same as 40 m3 of water at 100 m high.

As shown in Figure 1, the energy is stored/delivered when a controller adjusts the current, increasing or reducing it, which results in a voltage appearing in the terminals. The terminal voltage is regulated by the rate of change of the current, and can be adjusted by the regulator delivering or absorbing energy from the external circuits.[31]

SMES coils must be made of superconducting wires, which require being cooled at very low temperature. Typically, the operating temperature of the conductors is below 60 K or even lower (the liquid helium temperature is around 4 K) depending on the superconducting materials employed: High-Temperature Superconductors (HTS) or Low-Temperature Superconductors (LTS). New generation of SMES is focused on the use of HTS as these temperatures requires less refrigeration.

This system has a round-trip efficiency of about 95%. The most relevant advantage of SMES systems is related to the extremely high ramping that these systems allow. Power is available almost instantaneously and very high power output can be supplied in a short period of time. This feature is relevant, when comparing to other electricity storage options (e.g. pumped hydro storage or CAES) that present larger time delay (seconds to several minutes), taking into account the energy conversion from the stored mechanical energy back into electricity. Additionally, the loss of power is lower than for other storage technologies, since electric currents encounter almost no resistance.

Considering the intrinsic need for SMES refrigeration, with the consequent energy cost, as well as the high cost of superconducting wires, makes these systems fitted mostly for short duration energy storage and power demanding conditions. In view of that, SMES systems are currently being employed in situation in which there is a very high demand for power quality. Small SMES units are commercially available and larger projects are underway. Power quality control units have typically 1 MW, installed at manufacturing plants requiring ultra-clean power, like microchip production facilities.

Outside Europe, Northern Wisconsin (USA) transmission network has a well-known example of SMES installation for power grids applications, where a series of distributed SMES units was deployed to improve the transmission system stability. This transmission grid is subject to large and sudden load variations as result of an industrial process, which cause uncontrolled voltage fluctuations and voltage sag.

SMES systems are also used to provide grid stability in distribution grids. In Europe, there is a set of successful demonstration projects, namely in Germany, Finland and France, operating at 20 kW. Besides, pilot projects and research prototypes of SMES have also been

[31] *Joint EASE/EERA, "European Energy Storage Technology Development Roadmap," 2017. [Online]. Available: https://www.eera-set.eu/component/attachments/?task=download&id=312.*

designed in Italy, Germany, Finland and Spain.
SMES has been of scientific interest for years, yet it still requires a considerable amount of R&D effort to demonstrate the practical potential, especially for energy demanding applications.

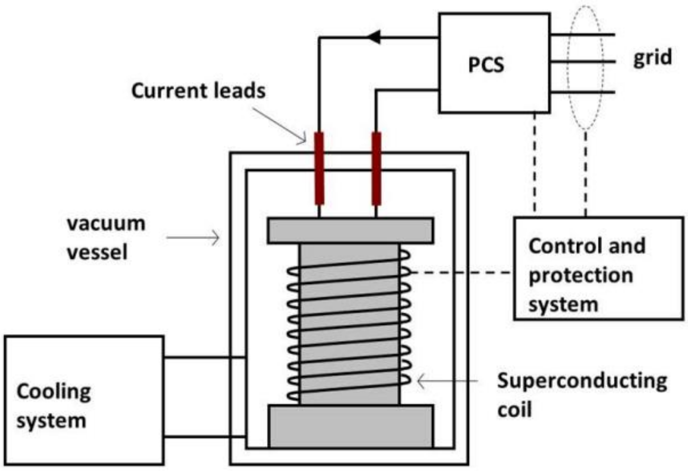


Figure 10: Schematic representation of a SMES system, including the Power Conditioning System (PCS), cryogenics and control and protection system, besides the superconducting coil[32]

9.2 Challenges (technical and economical) and outlook

Lowest score in PG table at Likelihood to achieve the Performance Goals through specific technologies

Score 1: Load response (long duration – days range)
Although it is conceptually possible to build SMES systems in the order of tens or hundreds of MWh range, most of these systems would be simply too large, requiring a huge cooling system, operating at extremely low temperatures (around 2K), making these projects impracticable. Seen this, without radical progress on high temperature superconductor's technology, it seems unlikely, at the current state of technology, to overcome the economic and technical challenges necessary to achieve long-term response.
Score 2: Load response (mid duration – hours range)
SMES is being effectively employed in short and mid-term applications, which require fast response and a high number of charge/discharge cycles. The response time of SMES stays within the millisecond range (virtually instantaneous) and usually are capable of providing this response from several minutes up to several hours. However, the low energy density is still one key characteristic that requires further development in order to make this a competitive technology in the mid-range response.
Score 2: Scalable – to cost-effectively build large-scale (e.g. MW) systems.
The limited number of existing SMES applications are mostly suited for power applications, which may explain the low number of investments received. For this reason, the maturity levels and technology costs didn't evolve much in recent years. The major barrier to the scalability of SMES is the relatively high costs and the production complexity compared with alternative technologies.
Score 3: Compact – Cost-effective improved Energy & Power density.
Although SMES have a high power to weight ratio (10-1000 kW/kg) as result of storage in superconducting coils, they present a relatively low energy to weigh ratio (around 3.5Wh/kg). Thus, the development of new high temperature superconductors that allow higher currents will contribute for the increase of the energy capacity and simultaneously to the reduction of the system overall losses.
Score 3: Safety
Some authors propose SMES units should be isolated at the 10 gauss (1 mT) level to keep unrestricted areas safe. European legislation[33], defines the limit of 5 Gauss (0.5 mT) as the limit to avoid causing interference with active implanted devices, e.g. cardiac pacemakers. As an example, in theory, for a full-size 5000 MWh SMES the magnetic field would decrease to 10 gauss at a radial distance of 2 km from the center of the coil. Other considerations related to the environmental impact of large SMES magnetic fields as well as the safety concerns on the use of large superconductor coils are also discussed[34].

9.3 Advantages and strong position

Highest score in PG table at Likelihood to achieve the Performance Goals through specific technologies

- Resuming, SMES have a very high performance in short duration, high power and high cycle applications.

32 Joint EASE/EERA, "European Energy Storage Technology Development Roadmap," 2017. [Online]. Available: https://www.eera-set.eu/component/attachments/?task=download&id=312.
33 DIRECTIVE 2013/35/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL, "Directive 2013/35/EU of 26 June 2013 on the minimum health and safety requirements regarding the exposure of workers to the risks," 2013. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32013L0035&rid=2.
34 C. Polk, R. W. Boom and Y. M. Eyssa, "Superconductive magnetic energy storage (SMES) external fields and safety considerations," in IEEE Transactions on Magnetics, vol. 28, no. 1, pp. 478-481, Jan. 1992, doi: 10.1109/20.119915.

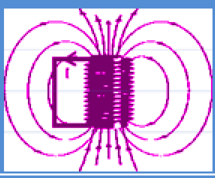
- .Overall, PGs where SMES score highest are the following:
- Load response – Short -duration (second - minutes), see above.
- Power quality: provides smooth electricity supply. The very fast response and virtually unlimited cycling capability makes this a very suitable solution. Commercially available SMES systems are mostly used for power quality purposes in high-tech industries which require ultra-high power quality (e.g. microchip manufacturers).
- Long lifetime. Most manufacturers declare a 30-year lifespan, which is independent from the duty-cycle.
- Flexibility & Modularity. SMES are easily combined with other flexibility sources (e.g. electrochemical storage, flywheels) contributing in the power support and ramping of the overall solution.

9.4 EU and National R&I projects and pilots

In the last decade, several successful R&D projects on SMES have been carried out in Europe.[35] However, there is currently no European commercial supplier of SMES. The main competences stay within R&D institutes, which have successfully developed several demonstrators and prototypes. Within the R&D project "Super SMES" in France, the Centre National de la Recherche Scientifique (CNRS) developed one of the first high-temperature superconducting SMES with a capacity of 800 kJ and 400kJ and Bi2212 material operating at 20 K36 (-253.15°C). Similarly, the Karlsruhe Institute of Technology (KIT) in Germany, developed a SMES hybrid concept, in combination with hydrogen, has been studied in detail.[36] The first small MgB2 superconducting coil has been built and tested. This combines the fast SMES operation with bulk hydrogen storage and seems interesting for large capacities with liquid hydrogen storage. In Spain, a consortium led by REESA built up two demonstrators in the context of the AMAS 500 project for grid quality operations. A new SMES project was launched in Italy with Columbus, ENEA, RES38, SPIN and the University Bologna to setup a 300 kJ, 100 kW SMES prototype system with MgB2 for a pioneering application in electricity systems.

9.5 Proposed target KPI

Table 8: Proposed targets for Superconducting Magnetic Energy Storage technology

Performance Goals 	**Challenges**	**KPI**	**Target 2025**	**Target 2031**
Load response – Mid duration (1-18 hours)	For MW scale SMES is challenging to go beyond 1 hour due to technical limitations.	• Duration in hours (time to charge, time to discharge)	• SMES > 1 MW – up to 3 hours	• SMES > 1 MW up to 6 hours
Scalable: to cost-effectively build large scale systems	SMES MW scale manufacturing process is expensive and complex. The current costs of materials for superconductors and the associated cooling system prevents the deployment of larger systems. Large R&D effort is needed to overcome these barriers.	• CAPEX €/kWh • Maturity of technology (TRL-MRL) and dependencies	• *CAPEX < 2000 €/kWh*	• *CAPEX < 500 €/kWh*
Compact: Cost-effective improved Energy & Power density	The low energy density of SMES systems is the most prominent barrier for the cost-effectiveness of this technology, when compared with other alternatives available.		• *1 MWh scale plants up to TRL 7-8*	• *5 MWh scale plants up to TRL 7-8*
Safety: safe operation	Safety concerns of SMES may jeopardise technology deployment.	There are not many commercial installations. It is difficult to have a reliable statistic on accidents	To be defined	To be defined

35 *European Energy Research Alliance (EERA), "Superconducting Magnetic Energy Storage," 2019. [Online]. Available: https://www.eera-energystorage.eu/component/attachments/?task=download&id=566:EERA_JPES_SP5_Factsheet_final.*
36 *M. Sander, R. Gehring and H. Neumann: LIQHYSMES—A 48 GJ Toroidal MgB2-SMES for Buffering Minute and Second Fluctuations, IEEE Transactions on Applied Superconductivity, Vol. 23, No. 3, 2013*

10. CHEMICAL

10.1 Short description of the technology

The large-scale penetration of renewable energy sources (RES) into the grid is crucial for the decarbonisation of the energy sector. However, significantly increasing the share of renewable power in the energy mix implies coping with the natural intermittency of RES like wind and solar. Moreover, RES cannot fulfil non-electric energy needs such as fuels for transportation and industry feedstock, which nowadays heavily rely on fossil fuels. Therefore, the conversion of surplus renewable electricity into chemicals in the form of a liquid or gas (power-to-liquid and power-to-gas) can be a smart way of addressing such intrinsic issues related to RES.

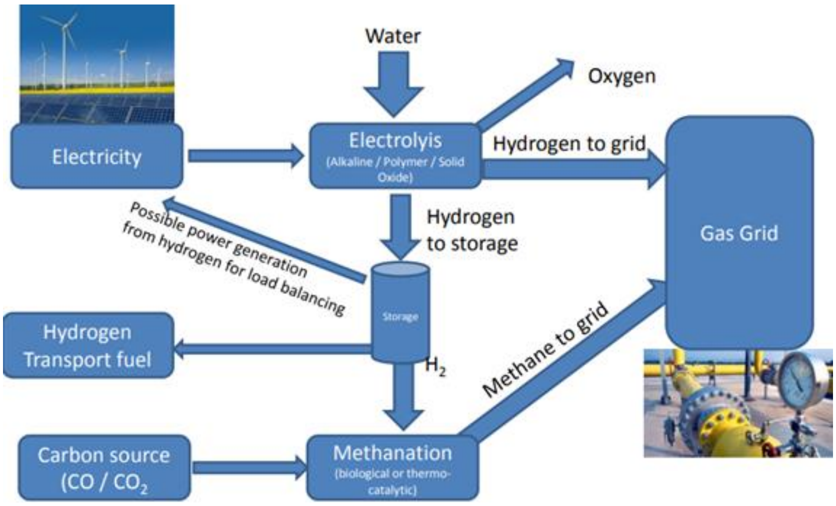


Figure 11: Role of H2 in the energy system

Hydrogen plays a crucial role for P2L and P2G technologies, since it is a very flexible energy carrier. Nowadays it is mainly produced from fossil fuels, so the process has a high carbon footprint, but in the mid-term, with the increase of RES share in the energy mix, it can be produced (mainly through electrolysis) in a carbon-neutral way.
Hydrogen can either be used directly (as a gaseous fuel for turbines, fuel cells and engines or directly as a chemical reactant for industrial needs) or indirectly (as an intermediate product for the generation of biofuels, methanol, ammonia, biogas, etc) to reduce the emissions from many sectors that are difficult to decarbonise (transport, power and heat generation, industries). In both ways, the transition from power to chemicals is an interesting way of storing energy, especially in those sectors where electrification isn't feasible. Using these chemicals instead of traditionally produced ones should not prove to be particularly difficult, since the chemical properties and compositions should remain very similar. Just some minor adjustments on final users need to be implemented and some safety issues (for example, when mixing hydrogen with natural gas in the grid) have to be taken care of. That said, the most important technical and economic progresses are needed in the P2X part, which should significantly benefit from scale economy in the near future.
The market maturity for electrolyzers, especially for hydrogen to be used in "hard-to-abate" sectors, is expected to be high due to increased availability of economically competitive options. However, the P2X2P sector will still be limited to specific frameworks. In the best case scenario, an optimistic but realistic estimate for Europe is around 40GW of installed electrolyzer capacity by 2030.IN THE BEST CASE SCENARIO

10.2 Challenges (technical and economical) and outlook

Lowest score in PG table at Likelihood to achieve the Performance Goals through specific technologies

The biggest issues to be addressed for this technology are related to the high number of passages from power to the final use, which imply many plant components (electrolysers, hydrogen storage facilities, plants for the conversion of hydrogen into other chemicals, distribution of chemicals to the final users). Therefore, the lowest scores are compactness (if we consider the whole process) and efficiency.
These are intrinsic issues of the technology. Nevertheless, the foreshadowed technological improvements of electrolysis (e.g., HT electrolysers) and other conversion processes (e.g., bio-methanation) together with scale economy, should help to achieve highest efficiencies and compactness.

10.3 Advantages and strong position

Highest score in PG table at Likelihood to achieve the Performance Goals through specific technologies
The highest scores are related to the capacity of the system to provide power even after long inactive periods, since the chemicals can be

stored even for long periods without significant losses, and the support the decarbonisation of many sectors that are difficult to decarbonise, especially the ones where electric alternatives are not applicable.
The plants are easy to maintain, but the regulatory framework related to hydrogen, gases and fuels needs to be updated and minor adjustments to the gas grid are necessary.

10.4 EU and National R&I projects and pilots

- SuperP2G (www.superp2g.eu)
- LivingH2 (https://www.dbi-gruppe.de/files/PDFs/Projekte/82_Projektsteckbrief_LivingH2_03SF0587B.pdf)
- HIGGS (www.higgsproject.eu)
- HEAVENN (www.heavenn.org)
- Store&Go (www.storeandgo.info)
- KEROGREEN (https://www.kerogreen.eu/index.php)
- ENABLEH2 (https://www.enableh2.eu/)
- RdS Italian project n.1.2 “Tecnologie dell’idrogeno” (https://www.mite.gov.it/pagina/ricerca-di-sistema-elettrico-nazionale) and many more

10.5 Proposed target KPI

Table 9: Proposed targets for chemical storage and conversion technologies

Performance Goals 	Challenges	KPI	Target 2025	Target 2031
Efficient: high enough conversion efficiency to cost-effectively integrate with necessary energy sources	The main drawbacks of the chemical storage technologies is efficiency, since a lot of passages (and, therefore, thermodynamic losses) are needed from power to the final product. Improvements can be made for the efficiency of the single components.	Alkaline Electrolyser efficiency PEM Electrolyser efficiency SOEC Electrolyser efficiency Fuel Cell efficiency (for transportation) Reduction of cost of production of ammonia from electrolysis Reduction of cost of production of methanol from electrolysis	*Too close to see significant improvements*	*From 63/70% to 65/71%* *From 56/60% to 63/68%* *From 74/81% to 77/84%* *From around 65% to 70%* *From 1100$/t to 1000$/t (800 in 2050)* *From850 $/t to 750 $/t (550 in 2050)*
Safe	Nowadays most of the applications’ safety issues are yet to be addressed properly. This is a crucial for flammable/explosive chemicals.		Blending of H2 and NG to be safe (and regulated) in the gas grid, as well as usage in various end users (up to H2 volumetric concentration of 20%)	First devices using 100% hydrogen to be operative Utilisation of alternative fuels in existing or slightly modified gas turbines, thermal plants, industries, etc… to be comparable with traditional fossil fuels in terms of safety First “pilot” planes, ships and trains to be operated with hydrogen without safety issues

Reversible Fuel Cells, electrolyzers directly fed with Renewable Energy Sources (RES) for off-grid applications, and the production processes of methanol and ammonia are some of the most promising short-term research and innovation (R&I) topics in the energy sector.

11. THERMAL

11.1 Short description of the technology

According to the storage principle, TES technologies are classified into three categories: sensible, latent, and thermochemical storage.

Sensible Heat Storage
Sensible heat storage is the most deployed and commercially advanced type of TES. It stores thermal energy by heating or cooling a storage medium (liquid or solid) without changing its phase. The amount of stored energy is proportional to the temperature change (rise or fall) on charging, within the operational temperature range, and the thermal capacity of the material. Sensible heat storage systems offer storage capacities ranging from 10 kWh to 50 kWh per tonne and storage efficiencies between 50% and 98%, depending on the specific heat of the storage medium and thermal insulation technologies. The working temperature range can go from -160°C to more than 1 000°C (European Association for Storage of Energy and European Energy Research Alliance, 2013).

Latent Heat Storage
Phase-Change-Materials (PCMs) use latent heat, which is the energy required to change the phase of the material (normally solid to liquid), to store thermal energy. There are many different types and applications of PCM. The main criterion for selecting a PCM is the phase-change temperature range needed for the application. In general, the actual level of phase-change temperature is leading into a categorisation:

- sub-zero PCMs (e.g., salt-water mixtures)
- Ice (0°C)
- Low temperature PCMs <120°C (e.g. paraffin waxes, salt hydrates)
- High temperature PCMs >120°C (e.g. inorganic salts and metal alloys)

Thermochemical Heat Storage
Thermochemical storage can be divided into reversible reaction-based storage and sorption-based energy storage (Aydin, Casey and Riffat, 2015). While sorption storage can only work up to temperatures of about 350°C, thermochemical systems without sorption can operate at higher temperatures and offer higher energy storage densities.

Technology and Application Matrix
The various technologies and their inherent physical boundaries offer a variety of applications in a variety of industrial environment. The following table differs the main application by required temperature level and maps industrial application to it. Further on available technologies are assigned by their technology readiness level to the application, reflecting the broad spectrum of Thermal Storage applications in the future energy landscape.

Table 10: Technology and application matrix for thermal storage (PHP: Power-to-Heat-to-Power; PH: Power-to-Heat)

	Application	Commercial	Demonstration	Prototypes/Applied research
High temperature (> 300 °C)	GRID • CSP • PHP	2-tanks molten-salt technology	Thermocline/Packed bed technology with low-cost filler materials (HTF: MS, oils, air)	Latent heat storage with anhydrous salts as PCMs Thermochemical storage (redox, CaO)
	INDUSTRY • PHP • PH		Thermocline/Packed bed technology with low-cost filler materials (HTF: air, oils)	
Medium temperature (120 - 250 °C)	INDUSTRY • PH (HPs, Joule heating)	Pressurised water tanks and steam accumulators	Latent heat storage with inorganic PCMs (anhydrous salts)	*Latent heat storage with organic or inorganic PCMs*
Low temperature (40 - 80 °C)	DOMESTIC – DH • PH (heating & DHW via heat pumps)	Water tanks	Latent heat storage with organic (e.g., paraffins, fatty acids ...) and inorganic (salt hydrates) PCMs Absorption systems	Thermochemical storage (salts hydration)

Brief description of commercial technologies

In the low and medium temperature range, there is a wide range of water-based technology options for domestic (non-pressurised tanks up to 90 °C) or industrial (steam accumulators up to 250°C) use. At 0°C, ice storage is commonly used both for domestic and industrial cooling applications. In the sub-zero temperature segment, also alcoholic-based thermal storage are commercially available for industrial purposes mainly. This segment hasn't been targeted by the given chapters.
In the temperature range up to 450°C there are commercial solutions using concrete as storage material.
At higher temperatures, customised solutions are commercially available for double tank molten-salt technology, mainly developed and used in CSP. The temperature range offered for these solutions is up to 550°C, limited by the current decomposition temperature of

commercially available salts.

As a novelty, packed-bed solutions with low-cost filling materials are becoming available. These are also tailor-made solutions offered by specialised companies. These solutions allow designs with working temperatures of up to 1000°C.
In the low temperature segment, sub-zero, also alcoholic-based thermal storage are commercially available for industrial purposes mainly. This segment hasn't been targeted by the given chapters.

11.2 Challenges (technical and economical) and outlook

Lowest scores in the table of Performance Goals (PG) are explained here and actions to improve them are presented according to applications.

High-temperature applications (CSP, PHP, PH)

Table 11:High-temperature applications (CSP, PHP, PH)

Challenges (lowest scores in PG)	Actions to face them
Extend load response duration to days-weeks	**CSP**: Makes no sense. Increasing storage capacity means increasing the size of the solar field. Too expensive **PHP & PH**: • Short-to-medium term (up to 2030): Develop high-performance thermal insulation solutions for sensible heat TES • Long-term (beyond 2030): Develop cost-effective, reliable high temperature thermochemical storage
Improve reliability (provide heat/power even after long inactive periods)	**CSP**: Develop new molten salts with much lower melting point **PHP & PH**: Not really a concern
Improve compactness	**CSP & PHP in the grid**: Limiting factors do not related to the TES system. Improving compactness involves reducing the size of the solar field (CSP) and power block (CSP, PHP). This could be achieved by next generation of s-CO2 power plants, which will require new TES solutions: • Short-to-medium term (up to 2030): Thermocline systems filled with low-cost sensible solid materials (or PCMs) using CO2 as working fluid • Long-term (beyond 2030): Develop cost-effective, reliable high temperature thermochemical storage based on e.g., carbonatation reactions **PHP & PH for high-temperature industrial applications**: In industry, the compactness of the TES system could be critical. In the short-to-medium term (up to 2030), significant increase of compactness could be achieved by: • Developing high-temperature latent heat storage systems, such as low-cost, PCM-based thermocline/packed-bed systems
Improve conversion efficiency	**CSP & PHP**: The efficiency is limited by thermodynamic cycles. In most commonly used Rankine cycles, improving efficiency involves increasing the inlet temperature to the turbine. In the short-to-medium term (up to 2030), this mainly will require: • Developing next generation of molten salts with increased operating temperature ranges (up to 600-700 °C) and performance • Develop alternative thermocline material cycles with low investment costs and long life time **PH**: Not concerned by this issue
Improve flexibility to integrate into infrastructures	**CSP**: For CSP there is no chance to modify existing assets with an implementation CSP. Derivates from CSP, e.g. CST (Concentrated solar thermal energy) could be used to enable heat provision into industries. **PHP & PH**: Not really a concern

Medium-temperature applications (PH in industry through either Joule effect or HPs)

Table 12: Medium-temperature applications (PH in industry through either Joule effect or HPs)

Challenges (lowest scores in PG)	Actions to face them
Improve compactness	Current TES technologies (pressurised water tanks and steam accumulators) are characterised by low energy density (30-60 kWh/m3), which limits the usability. In the short-to-midterm (up to 2030), significant increase of energy density could be achieved through: • Development of cost-competitive latent heat storage systems, such as low-cost, PCM-based thermocline/packed-bed systems

	• Advanced steam accumulators integrating PCM materials development
Improve flexibility to integrate into infrastructures	Propose efficient solutions for efficient power-to-heat conversion with integrated TES capacity: • Development of cost-competitive latent heat storage systems with suitable design for integration into heat pumps • Development of Joule effect-based power-to-TES interfaces (compact heat exchangers) or, alternatively, develop PCM materials with capacity to directly convert electricity into heat

Low-temperature applications (PH in buildings or DHs through HPs)

Table 13: Low-temperature applications (PH in buildings or DHs through HPs)

Challenges (lowest scores in PG)	Actions to face them
Improve compactness at competitive cost	Most currently used TES technologies (water tanks) is characterised by low energy density (60 kWh/m3 max.) and has negative effect in the HP´s COP (sensible heat). Existing latent heat-based technologies can solve these two issues but still are too expensive: • Development of cost-competitive latent heat storage systems, such as low-cost, PCM-based packed-bed systems

11.3 Advantages and strong position

Highest score in PG table at Likelihood to achieve the Performance Goals through specific technologies

TES advantages: mid duration load response, smooth power/heat supply, robustness, long lifetime, scalable, safety, sustainability – Based on the physical working principle thermal storages are compared to other technologies slower in their reaction time, which leads to both advantages as well as disadvantages. Once discharging process is in operation the thermal inertia leads to a robustness against short-term fluctuation the demand side.
In addition, thermal storages offer certain advantages in environments that need both heat and electricity. In such applications the amount for one or the other commodity can be adjusted by mass flow control and can be shifted smoothly in every direction.
The physical setup and materials used (e.g., water, solid materials) provide a high level of robustness to changing environments as well as their handling of the course of operations. Based on limited degradation over time, as mainly the heat storage capacity is insusceptible to physical and limited chemical influence, thermal storages guarantee a long lifetime.
Pending on the temperature level used in the storage itself the energy density is high and offers through simplicity of materials a scalability, which is purely limited by the available space and surrounding equipment capabilities (e.g., heat exchangers, valves).
Most of the thermal storages are utilising vastly available and environmentally friendly materials, which offers cost-wise as well as regarding sustainability advantages.
Besides the risk of contact with high temperatures (and partially high pressures), thermal storages are considered as safe, as no hazardous materials or materials with a high chemical reaction potential are used.
STRONG POSITION compared to other technologies:
The major advantages of the thermal storage technology as compared to other storage technologies are related to the relevance of the thermal energy use of consumption as compared to other forms of energies that together with the opportunities to offer higher levels of flexibility offers the following differential values:

- Support decarbonisation of industrial process heat and residential heating/DHW needs (Power-to-heat) while contributing to enhance grid flexibility
- Compactness – kWh/m3 (much higher than many other technologies)
- Cost - €/kWh (much lower than that of many other technologies)

SHORT-TO-MIDTERM (up to 2030) IMPROVEMENTS – Increasing compactness while decreasing cost

Table 14: Reference technologies for thermal storage and possible pathways for improvement

Reference technology	Improvement possible pathways
Two-tank molten salt technology for high-temperature applications (> 300 °C)	Increase compactness and reduce cost by developing single-tank TES systems such as thermocline system with low-cost filler materials (either sensible solid materials or high-temperature PCMs) compatible with molten salts Reduce cost and increase energy density by pushing the development of thermocline systems with low-cost filler materials (either sensible solid materials or high-temperature PCMs) using other HTFs than MS, with additional advantage of higher working temperatures
Steam accumulators for medium-temperature applications (120-250 °C)	Development of advanced steam accumulator integrating PCMs within - Thermocline systems with low-cost filler PCMs using water-steam as HTF
Water tanks for low-temperature applications	Development of cost-affordable compact latent heat storage for integration into HPs

(40-80 °C)	

11.4 EU and National R&I projects and pilots


Andasol-3, Spain

TWO-TANKS MOLTEN SALT TECHNOLOGY (Up to 550 °C approx.)

Country	CSP power plant	Net capacity (MW)	Thermal energy storage (hours)
Spain	Manchasol-2	50	7.5
	Andasol-3	50	7.5
	Termesol 50	50	7.5
	La Florida	50	7.5
	La Dehesa	50	7.5
	Casablanca	50	7.5
	Termosol 2	50	9
	La Africana	50	7.5
	Gemasolar	20	15
Morocco	NOOR III	134	7
South Africa	Xina Solar One	100	5.5
	Khi Solar One	50	2
	Bokpoort	50	9.3
	Kathu South Africa	100	4.5
India	KVK Energy Solar	100	4
USA	Crescent Dunes	100	10
	Solana	250	6
Kuwait	Shagaya CSP Plant	50	10
India	Supcon Solar	50	6

Table 15: Reference Projects for thermal storage

FIXED PACKED-BED TECHNOLOGY WITH LOW-COST FILLER MATERIALS

BRENMILLER ENERGY

Several real-scale TES plants using crushed rocks as filler materials and air as heat transfer fluid:
23 MWh for steam generation, ENEL, Italy
10 MW in Purchase College of the State University of New York, USA
90 MWh in ROTEM-1 CSP plant, Israel

SIEMENS Gamesa
RENEWABLE ENERGY

Biggest German public funded storage R&D project. Partners: Siemens, TUHH, Hamburg Energie – Connected to the Hamburg grid in June 2019

Demonstrator with **130 MWh storage capacity** and a **5.4 MW** resistive heater in Hamburg-Altenwerder - Filler material: crushed basalt; HTF: air.

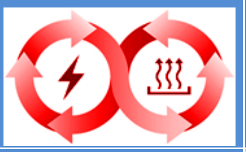
ORC-PLUS
DISPATCHABLE SMALL-SCALE SOLAR THERMAL ELECTRICITY

H2020 Project (ID: 657690)

Demonstrator with **20 MWh storage capacity** with magnetite ore as filler material and synthetic oil as HTF – CSP plant at Ben Guerir, Morocco.

11.5 Proposed target KPI

Table 16: Proposed targets for Thermal storage technology

Performance Goals 	Challenges	KPI	Target 2025	Target 2031
Reliable: to provide power even after long inactive periods	Current molten salt storage technology has the problem of solidification of salts at temperatures below their crystallisation point. Reducing this point would help to manage the plant during shutdown periods and reduce the corresponding energy consumption. Due to thermal losses, all sensible heat storage technologies have storage periods ranging from hours to a few days. Improving thermal insulation would allow storage periods to be extended.	Storing periods without self-discharging	New high-temperature thermal insulation materials that reduce thermal losses by half at competitive prices.	New salts with lower melting/crystallisation point (< 120 °C).
Long lifetime	There is still little information on the lifetime of emerging technologies (e.g., high temperature packed-beds, latent heat storage).	Number of cycles	Prove > 10000 for packed-bed system with low-cost filler materials	*Prove > 5000 for latent heat storage technologies*
Scalable: to cost-effectively build large-scale (MW) systems	Whatever the storage technology as well as the application, CAPEX reduction is a priority. For emerging technologies, demonstrators are needed.	CAPEX (€/kWh)	Demonstrators (MW scale) both for power-to-heat and power-to-heat-to power applications	CAPEX < 10 €/kWh for high temperature sensible heat storage CAPEX < 25 €/kWh for high temperature latent heat storage CAPEX < 60 €/kWh for low & medium temperature latent heat storage
Compact: cost-effective improved energy density	Compactness is of paramount importance in applications where space is a limiting factor (e.g., industrial heat and buildings). It also contributes to reduce	Energy density (kWh/m3)	200 kWh/m3 for high-temperature applications	> 350 kWh/m3 for high-temperature applications

	CAPEX by allowing lower tanks and HX size.			
Efficient: high-enough conversion efficiency to cost-effectively integrate with energy sources	In CSP and PHP, the efficiency is limited by thermodynamic cycles. In most commonly used Rankine cycles, improving efficiency involves increasing the inlet temperature to the turbine.	Round-trip efficiency	Packed-bed systems with low-cost filler materials working at temperatures > 800 °C	Next generation of molten salts with increased operating temperature ranges (up to 600-700 °C) and performances

12. CONCLUSIONS

This report presents a map that can be used for a number of different purposes. The most common and actual demand is to determine the duration and type of storage needed to make the electricity grid system more flexible and reliable with a high penetration of renewable energy sources. Other uses of the map could include replacing peaker gas-fired plants, addressing and reinforce weak points in the electricity system, and reducing emissions from energy-intensive industries (some of these examples are illustrated in the Annexes). Whatever the specific purpose, the solution that meets the performance goals will usually involve a combination of different storage and conversion technologies. The aim of this report is to identify the weaknesses of each storage and conversion technology in an agnostic manner and to propose specific targets to address them, using the available evidence to guide research and development efforts. Where possible, these targets are associated with a Technology Readiness Level (TRL).
However, it's important to note that the achievement of these objectives at European level depends on the presence and strength of European players in the value chain of each technology. A strong European presence can ensure that the necessary resources and expertise are available to develop and commercialise the technology. To give an indication of the level of investment and interest in a particular technology, a list of European and national projects for specific Member States is provided for each technology.

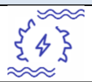
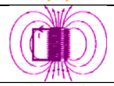
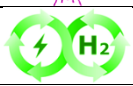
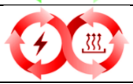
As is often emphasised in the relevant literature, successful innovation needs to integrate economic, regulatory and technical considerations. It's worth noting that some of these technologies are already proven and available for commercial deployment, while others require further research, development and demonstration and may not be commercially available before 2030. This underlines the importance of investing in research and development to bring these technologies to maturity and the required scale. In addition, regulatory and legislative barriers may also play a critical role and prevent the implementation of the solution despite the maturity of the technology. This underlines the importance of promoting a favourable regulatory environment to facilitate the deployment of new technologies.

Considering the process of technology innovation described in terms of the following five distinct stages:

I. Idea creation
II. R&D
III. Engineering at pilot scale
IV. Technology demonstration
V. Deployment

the table below summarises our findings on the state of innovation for different storage and conversion technologies, although there may be some uncertainty about the pace and nature of innovation for some of them.

Table 17: Summary of study findings on the current innovation status of selected technologies

Technology	Current innovation status					Chapter
	I (Idea creation)	**II** (R&D)	**III** (Engineering at pilot scale)	**IV** (Technology demonstration)	**V** (Deployment)	
				X	X	5
			X	X		6
			X	X	X	7
		X	X	X		8
	X	X				9
	X	X	X	X		10
		X	X	X		11

ANNEXES

The following tables in this annex display the mapping exercise.

The **Tables A1.1 and A1.2** are mapping how important are the performance aspects of the storage technologies with respect to the different Use Cases. The scoring ranges from “No Important: 1” to “Highly important: 5” passing through “No important except some situations: 2” and “Very important except some situations: 4”, with an intermediate score of 3 and NA=Not Applicable case, when there is no link at all.

The **Table A2** links the Performance Goals to the specific energy storage and sector coupling conversion technologies. The question that this part of the mapping attempt to answer is how likely it is that a Performance Goal could be achieved by the specific technology. The mapping will most likely represent the state of the art of the technology, but for the lower scores it also incorporates some level of expectation.

The scoring ranges from “Very Unlikely: 1” to “Highly likely: 5” passing through “Unlikely except some situations: 2” and “likely except some situations: 4”, with an intermediate score of 3, NA=Not Applicable case when the technology does not apply. Uncertain score marked with a (?) meaning that more information is required to answer the question.

A low score highlights a challenge that the technology should overcome to make it suitable for achieving the specific Performance Goal. A low score also highlights an opportunity for the technology to improve its performance through R&I actions. The table also incorporates an assessment of whether the technology has room for improvement based on its level of maturity and whether actions are considered on the different time scales of 2025 and 2031.

Performance Goals must be supported by quantitative, ambitious, and realistic targets. The metrics through which the targets are measured are defined in a set of KPIs, and the **Table A3** traces the links between Performance Goals and the defined KPIs.

Some examples of how to use the mapping tables

Storage needed to make the electricity grid system more flexible and reliable with a high penetration of renewable energy sources

A scenario of high penetration of renewable energy sources scenario in the electricity system place certain demands on the different use cases and actors involved. On the **Generation** side the main aspects to be considered are “*Electric Supply Capacity*” and “*Curtailment minimization*”. On the **Transmission** side the most relevant aspect could be the “*Transmission investment deferral*”. On the **Distribution** side “*Capacity support*”, “*Contingency grid support*” and “*Intentional islanding*” will be relevant and most of the **Ancillary** services will be required. On the **Costumer** side “*Peak shavings*”, “*Maximization of self-production and self-consumption*” and “*Continuity of energy supply*” will need to be maximized. For the Generation, Transmission, Distribution and Costumer side, the storage and conversion technologies that can support all these requirements should be the best performing especially for Mid (hours range) and Long duration (days, weeks range) load response, Power quality and Reliability while for most of the Ancillary services the selected technology should be the best performing for the short duration load response (See Table A1.1 and A1.2).

Not all technologies are able to meet all these requirements. Therefore, the solution is often a combination of different storage and conversion technologies. If the focus is on long duration (days, weeks range) load response, we can see that PHP and H2 (P2G) are both very well suited technologies to achieve "long duration load response", but then what is required to ensure it? We need to consider a medium/long term strategy with R&I actions. PHP is a very mature technology, while H2 is not yet established at the required scale. From the mapping, the result of the prioritisation exercise for PHP is to improve the "Scalability" Performance Goals, while for H2 it is to improve the "Efficiency" and "Safety" Performance Goals (see Table A2). Improving these performance goals should be prioritised over others.

Replacing gas-peakers

To replace gas turbines (gas-peakers) and still provide flexibility and capacity firming, the use case is this time on the **Distribution** side with “*Capacity support*” and “*Contingency grid support*”. The main performance goals are then Mid duration load response, Long lifetime and Robustness (see Tables A1.1 and A1.2). The technologies most likely to meet these performance targets are PHP, H2, Battery and CAES (see Table A2).

For PHP, barriers may be of an administrative nature related to permitting and time to deployment, while for the other technologies barriers may be related to availability of technology providers and supply chain issues. In this particular example, there is another aspect to consider. An asset (gas speaker) needs to be replaced/relocated, which may lead to resistance from the owner of the asset and the supplier of the primary energy required for its operation. In this case, gas could be excluded as a less sustainable solution if the emphasis is placed on improved efficiency and sustainability.

A1.1. Importance of performance goals to the use case

Performance GOALS	Load response – Short - duration (second - minutes)	Load response – Mid - duration (1 - 18 hours)	Load response – Long - duration (days - weeks)	Power quality: provides smooth electricity supply.	Reliable: – can provide power, even after long inactive periods.	Robust: able to withstand extreme use conditions (e.g temperature)	Long lifetime	Scalable: to cost-effectively build different scale systems	Compact: Cost-effective improved Energy&Power density	safe	Efficient: high enough conversion efficiency to cost-effectively integrate with necessary energy sources	High material efficiency and sustainable end of life management	Flexible: able to integrate into infrastructure (boundary constraints assessment)	Modular: can combine with other storage technologies	Support to the decarbonization of industrial, power production, transport and residential needs
Generation	Importance of performance goals to the use case														
Arbitrage	○	●	◔	○	◑	◔	◕	◕	○	◑	◕	◑	◔	◔	NA
Electric supply capacity	○	◑	●	◕	●	◑	◕	◕	◔	◑	◕	◑	◕	◕	NA
Support to conventional generation	◑	●	○	◑	◔	◕	◑	◔	◔	◑	◑	◑	◕	◕	NA
Ancillary services RES support	◑	○	○	◕	◔	◑	◑	◔	◑	◑	◑	◑	◕	◕	NA
Capacity firming	◔	●	○	◕	◔	◑	◑	◑	○	◔	◑	◑	◑	◔	NA
Curtailment minimisation	◔	●	○	◕	◑	◑	◑	◑	○	◔	◑	◑	◑	◔	NA
Limitation of disturbances	◕	○	○	◕	○	◑	◑	◔	○	◔	◑	◑	◑	◔	NA
Ancillary	Importance of performance goals to the use case														
Primary frequency control (FCR)	●	○	NA	NA	○	○	◑	◔	◔	◔	◑	◑	◕	◔	NA
Secondary frequency control (aFRR)	◕	◔	NA	NA	○	○	◑	◔	◔	◔	◑	◑	◑	◔	NA
Tertiary frequency control (mFRR & RR)	◕	◑	NA	NA	○	○	◑	◔	◔	◔	◑	◑	◑	◔	NA
Frequency stability of the system	●	NA	NA	NA	◔	◑	◑	◕	◔	◑	◑	◑	◕	◑	NA
Black start	●	◕	○	NA	●	◕	◔	◔	◔	◔	◔	◑	◑	◑	NA
Voltage support	●	◑	NA	◕	○	○	◑	◔	◔	◑	◔	◑	◕	◑	NA
New ancillary services	●	◑	NA	NA	○	○	◑	◕	◔	◑	◔	◑	◕	◑	NA
Congestion management	●	◑	NA	◕	○	○	◑	◕	◔	◑	◔	◑	◕	◑	NA
inertia response/spinning reserve	●	◑	○	◕	◔	◑	◔	◔	◔	◔	◔	◑	◕	◔	NA
Transmission	Importance of performance goals to the use case														
Transmission investment deferral	○	◔	◔	◕	◑	◕	◕	◕	◑	◔	◑	◑	●	◑	NA
Angular stability	◕	◔	NA	◕	◑	◕	◑	◕	◑	◔	◑	◑	●	◑	NA
Transmission support	NA	◑	NA	◕	◑	◕	◑	◕	◑	◔	◑	◑	●	◑	NA

NA	Not Aplicable
○	No relavant
◔	No relevant except some situations
◑	Relevant
◕	Higly relevant except some situations
●	Highly relevant

A1.2. Importance of performance goals to the use case

Performance GOALS	Load response – Short - duration (second - minutes)	Load response – Mid - duration (1 - 18 hours)	Load response – Long - duration (days - weeks)	Power quality: provides smooth electricity supply.	Reliable: – can provide power, even after long inactive periods.	Robust: able to withstand extreme use conditions (e.g temperature)	Long lifetime	Scalable: to cost-effectively build different scale systems	Compact: Cost-effective improved Energy&Power density	safe	Efficient: high enough conversion efficiency to cost-effectively integrate with necessary energy sources	High material efficiency and sustainable end of life management	Flexible: able to integrate into infrastructure (boundary constraints assessment)	Modular: can combine with other storage technologies	Support to the decarbonization of industrial, power production, transport and residential needs
Distribution	Importance of performance goals to the use case														
Capacity support	NA	●	NA	NA	NA	◑	●	NA	NA	NA	NA	NA	NA	NA	NA
Contingency grid support	NA	●	NA	NA	NA	◑	NA	NA	NA	NA	NA	NA	NA	NA	NA
Distribution investment deferral	◑	◑	◔	NA	NA	◑	NA	NA	NA	NA	NA	NA	NA	NA	NA
Distribution power quality	●	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Dynamic, local voltage control	◕	◑	NA	◑	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Intentional islanding	◑	◕	●	◕	◑	◕	●	●	◑	◕	◕	◕	●	●	NA
Limitation of disturbances	◑	NA	NA	◑	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Reactive power compensation	◑	NA	NA	◑	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Customer	Importance of performance goals to the use case														
End-user peak shaving	◔	●	●	NA	NA	NA	◕	◔	NA	◕	◕	◕	◑	◔	NA
Time-of-use energy cost management	○	●	◔	○	◑	◔	◕	◕	○	◑	◕	◑	◔	◔	NA
Particular requirements in power quality	NA	NA	NA	●	NA	NA	NA	NA	NA	◕	NA	◕	◑	◔	NA
Maximising selfproduction & selfconsumption of electricity	◔	●	●	NA	NA	NA	●	NA	NA	◕	NA	◕	◑	◔	NA
Demand charge management	NA	NA	NA	NA	NA	NA	◑	NA	NA	◕	NA	◕	◑	◔	NA
Continuity of energy supply	◔	●	◑	NA	NA	NA	◑	NA	NA	◕	NA	◕	◑	◔	NA
Limitation of upstream disturbances	NA	NA	NA	NA	NA	NA	NA	NA	NA	◕	NA	◕	◑	◔	NA
Reactive power compensation	NA	NA	NA	NA	NA	NA	NA	NA	NA	◕	NA	◕	◑	◔	NA
EV integration	●	◕	○	●	●	●	◑	NA	NA	◕	NA	◕	◕	◔	NA
Thermal Service	Importance of performance goals to the use case														
Space Heating and Hot Water Production	NA	◕	◕	NA	◔	●	◑	◑	◑	◕	◕	◕	●	NA	●
Heat to Power	NA	◑	◕	◔	◔	●	●	◑	◑	◕	◔	◑	◑	◔	◕
(Industrial) Process Heat	NA	◕	◕	NA	◔	●	◕	◕	◑	◕	●	◕	●	NA	●
Chemical Service	Importance of performance goals to the use case														
Chemical to industrial process	○	◕	◕	NA	◑	◔	●	●	◑	●	◕	◔	●	NA	●
Chemical to heat	◔	◑	◕	NA	◑	◔	●	◑	◑	●	◑	◔	◕	NA	◔
Chemical to power	◕	◕	◕	◕	◑	●	●	◕	◑	●	●	◔	◕	◑	◕
Chemical to mobility	●	●	◑	NA	●	●	◕	◔	●	●	◕	◕	●	◔	◕

NA	Not Aplicable
○	No relavant
◔	No relevant except some situations
◑	Relevant
◕	Higly relevant except some situations
●	Highly relevant

A2. Likelihood to achieve the performance Goals & State of the Art / Room for improvements and R&I actions

Performance GOALS		Load response – Short - duration (second - minutes)		Load response – Mid - duration (1 - 18 hours)		Load response – Long - duration (days - weeks)		Power quality: provides smooth electricity supply.		Reliable: – can provide power, even after long inactive periods.		Robust: able to withstand extreme use conditions (e.g temperature)		Long lifetime		Scalable: to cost-effectively build different scale systems		Compact: Cost-effective improved Energy&Power density		safe		Efficient: high enough conversion efficiency to cost-effectively integrate with necessary energy sources		High material efficiency and sustainable end of life management		Flexible: able to integrate into infrastructure (boundary constraints assessment)		Modular: can combine with other storage technologies		Support to the decarbonization of industrial, power production, transport and residential needs	
Technologies		**Likelihood to achieve the performance Goals & State of the Art / Room for improvements and R&I actions**																													
Electrochemical (battery)		◕		◕		○		◕		◑		◑		◑		◕		◑		◕		●		◑		◕		◑		◕	
Chemical	P2-Gas-2P	◔	↓	◕		◕		◕		◕		◔	→	◔	→	◑		○	↓	◑	→	○	→	◑		◕		◔	→	◕	
	P2-Liquids-2P	◔	↓	◕		◕		◕		◕		◕		◕		◑		◑		◑	→	◔	→	◕		◕		◑		◕	
Chemical	P2-Gas-2Industry (as gas, to heat)	NA		◑		◕		NA		◕		◑		◑		◕		◔	↓	◑		◑		◕		◕		NA		●	
	P2-Liquid-2Industry (as liquid, to heat)	NA		◑		◕		NA		◕		◑		◑		◕		◔	↓	◑		◑		◕		◕		NA		●	
Chemical	P2-Gas-2Mobility	◕		◕		◕		NA		◕		◑		◑		◑		◔	↓	◑		◔	→	◑		◔	→	◕		◕	
	P2-Liquid-2Mobility	◕		●		●		NA		◕		◕		◕		◕		◑		◑		◔	→	◕		◔	→	◕		●	
Thermal	P2Heat2P	NA		◕		◔		●		◑	→	◕		●	→	◕	↑	◔	↑	◕		◑	↑	◕		●		◕		◑	
	P2Heat (e.g. heat pump)	NA		◕		○		●		◑	→	◕		●	→	◕	↑	◔	↑	●		◑	↑	◕		◕		◕		●	
	CSP (Concentrated Solar Power)	◕		◕		○		●		◑	↑	◕		●		●		○		◕		◑	↑	◕		◔		◕		◕	
Mechanical	Compressed air (CAES)	NA		◑	↑	◔	→	◕		◕		◕		◕		◑	↑	◕		◕		◔	↑	◕		◑	↑	◕		NA	
	Flywheels	●		○	↓	NA		●		◕		●		●		◔	→	◑	→	◔	→	◕	→	◕		◑	↑	●		◑	→
	Pumped hydropower (PSH)	●	→	●	→	●	→	●	→	●	→	●	→	●	→	◑	↑	●	→	●	→	●		●	→	◑	↑	◕	↑	NA	
Electromagnetical (Superconducting magnetic ES (SMES)		●		◔	→	○	↑	●		◕		?		◕	→	◔	↑	◑	→	◑	→	◕	→	◕	→	◕	→	◕	→	◕	→
Electric (Supercapacitor)		●		○	↓	NA		●		◕		?		●	↓	◕	→	◑	↑	◕	→	●	→	◕	→	◕	→	●	→	◑	→

NA	Not Aplicable
○	Very Unliikely
◔	Unliikely except some situations
◑	
◕	liikely except some situations
●	Highly liikely
?	Uncertain. More information required

Color code: Actions
No action
Action 2025
Action 2031
Action 2025/2031

Room for improvemnt- linked to the level of maturity	
↓	No room for improvement foreseen
→	Some room for improvement - possible game changer or little improvements easily foreseen
↑	Plenty of room for improvement

A3. Relevance of KPI and metric for the Performance Goals assessment

Performance GOALS	Load response – Short - duration (second - minutes)	Load response – Mid - duration (1 - 18 hours)	Load response – Long - duration (days - weeks)	Power quality: provides smooth electricity supply.	Reliable: – can provide power, even after long inactive periods.	Robust: able to withstand extreme use conditions (e.g temperature)	Long lifetime	Scalable: to cost-effectively build different scale systems	Compact: Cost-effective improved Energy&Power density	safe	Efficient: high enough conversion efficiency to cost-effectively integrate with necessary energy sources	High material efficiency and sustainable end of life management	Flexible: able to integrate into infrastructure (boundary constraints assessment)	Modular: can combine with other storage technologies	Support to the decarbonization of industrial, power production, transport and residential needs
KPIs	Relevance of KPI and metric for the Performance Goals assessment														
Lifetime (n. of cycle)	NA	NA	NA	NA	NA	NA	✓	NA	NA	NA	NA	NA	NA	NA	NA
Lifetime (n. of years)	NA	NA	NA	NA	NA	NA	✓	NA	NA	NA	NA	NA	NA	NA	NA
Performance (specific power) - W/kg - L - m2	NA	NA	NA	NA	NA	NA	NA	NA	✓	NA	NA	NA	NA	NA	NA
Performance (specific energy) - Wh/kg - L - m2	NA	NA	NA	NA	NA	NA	NA	NA	✓	NA	NA	NA	NA	NA	NA
Efficiency (Round trip efficiency: %)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	✓	NA	NA	NA	✓
Safety (e.g number events and severity)	NA	NA	NA	NA	NA	NA	NA	NA	NA	✓	NA	NA	NA	NA	✓
Maturity of technology (TRL-MRL) and dependencies	NA	NA	NA	✓	NA	✓	NA	✓	NA	✓	✓	✓	✓	✓	✓
Time for deployment (months - years - decades)	NA	NA	NA	NA	NA	NA	NA	✓	NA	NA	NA	NA	✓	✓	✓
Storing period: hours - days - weeks and self discharge	NA	NA	NA	NA	✓	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
short/long/seasonal terms: duration in hours - days - weeks (time to charge, time to discharge)	✓	✓	✓	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Calendar life	NA	NA	NA	NA	✓	NA	✓	NA	NA	NA	NA	NA	NA	NA	NA
Time response	✓	✓	NA	NA	✓	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Ramp up (W/sec curve)	✓	✓	NA	NA	NA	NA	NA	NA	NA	NA	✓	NA	NA	NA	NA
Availability: downtime foreseen (e.g. Maintenance) + Reliability (unforeseen events) - (%)	NA	NA	NA	✓	✓	✓	NA	NA	NA	NA	NA	NA	NA	NA	✓
CAPEX, OPEX (maintenance only), Tot. OPEX (Euro/kWh) Energy based	NA	NA	NA	NA	NA	NA	NA	✓	NA	NA	NA	NA	NA	NA	✓
CAPEX, OPEX (maintenance only), Tot. OPEX (Euro/kW) Power based	NA	NA	NA	NA	NA	NA	NA	✓	NA	NA	NA	NA	NA	NA	✓
ESOI ratio	NA	NA	NA	NA	NA	NA	✓	NA	NA	NA	✓	✓	NA	NA	NA

NA	Not aplicable
✓	Applicable

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